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STUDY OF AN ATTITUDE CONTROL SYSTEM FOR THE ASTRONAUT MANEUVERING UNIT

by W. E. Drissel, R. L. Haines, R. J. Kell, D. N. Lovinger, and D. M. Moses

Prepared under Contract No. NASw-841 *by*
HONEYWELL, INC.
Minneapolis, Minn.
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1965

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FOREWORD

The program, "Study of an Attitude Control System for the Astronaut Maneuvering Unit" began in December 1963 and ended in July 1964. It was conducted by Honeywell Inc., under NASA Contract NASw-841.

Messrs. David Middleton and Lowell Anderson served as Technical Monitors for the National Aeronautics and Space Administration. Mr. Robert Kell was the Honeywell Project Engineer. The NASA Contracting Officer was Mr. W. Collins, Jr. The Honeywell Program Administrators were Messrs. A. Braun, J. Damiani, and L. D. Kuechenmeister. Messrs. W. E. Drissel, R. L. Haines, R. J. Kell, D. N. Lovinger, and D. M. Moses wrote the final report.

Messrs. K. Rapp, G. Greer, H. Kent, R. Kirk, and O. Pomeroy also worked on the program.

Mrs. M. Larson and Mr. R. Benson prepared the manuscript for publication.

ABSTRACT

This report describes the work done under a study contract whose objectives were to study Attitude Control Systems (ACS's) for Astronaut Maneuvering Units (AMU's) and to define in detail the most nearly optimum system for the application. Detailed definition included identification or specification of principal components, and specification and drawing layout of all circuitry.

The system uses a voice-operated controller for both attitude and translational control, three floated integrating gyros for attitude sensing, a fixed pulse and pseudo-rate control system, and eight reaction jets.

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TECHNICAL DISCUSSION

This volume comprises the final report of work performed under NASA Contract No. NASw-841, "Study of Attitude Control System for Astronaut Maneuvering Unit." Appendix A consists of the specifications developed under the contract. Appendix B consists of the instrumentation and circuit drawings developed under the contract.

SECTION I
INTRODUCTION

Future space missions will require astronauts to leave their spacecraft and travel to a target. Once there, they will perform a work task, such as inspection or assembly, and then return to the spacecraft. It is assumed that, for the foreseeable future, astronauts will perform this maneuver by orienting mass expellant jets and applying translational thrust. During an orbital transfer, translational thrust will be required for error correction.

The problem of man's maneuvering in space was approached with full recognition that it is highly demanding on human capabilities. The problem is equally demanding on the type of reliable and precision equipment which must be provided to the astronaut for the successful completion of his mission.

Much research has been conducted on specialized individual propulsion units, small life support systems, and human capabilities in space. Honeywell's contribution to this challenge, as documented herein, will have been to:

- Provide NASA with a conceptual design (with specifications and instrumentation drawings) of an attitude control system (ACS) suitable for an astronaut maneuvering unit (AMU).

- Provide NASA, through various research, analyses and trade-off considerations, with clear impressions of how Honeywell's conceptual design was evolved and established.

- Provide NASA with a clear understanding of the problems encountered (or extensions of problem areas) in striving for a workable design for an ACS.

- Recommend problem solutions which will provide NASA with a basis for future AMU program planning offering the most benefit with the least investment.

The first portion of the Honeywell task (reported in Section II) entails a survey of the state of the art, especially the human factors area, to determine what tasks and constraints had been previously anticipated. Of particular significance, it was found that an ideal controller had not been conceived and that a satisfactory guidance scheme for use under realistic AMU conditions had not been developed. Also, the survey of the guidance scheme was extended only so far as necessary to determine the requirements imposed upon the attitude control system. The next portion (Section III) contains a discussion of the general considerations and assumptions underlying the study.

The investigation of the controller (Section IV) resulted in the definition of a voice-operated controller, in sufficient detail to determine feasibility. It is significant, however, that the conceptual design of the ACS does not necessarily require voice control. The ACS (as described in Section V) can use either discrete or continuous command obtained with a conventional "stick" type controller or any other suitable concept.

The attitude sensors and electronics portion of the ACS was defined (Section V) in such detail that breadboard circuits can be built from prints and drawings (which are shown in **Appendix B**). It should also be pointed out that reliability engineering (as discussed in Section VI) was included as an integral part in this study program.

Definition of problems defined and recommendation for future studies are included in Section VII

SECTION II
STATE-OF-THE-ART SURVEYS

At the outset of the program, an investigation was undertaken of work done on earlier AMU programs and related programs. Purposes of this investigation were:

- To define tasks which will be assigned to an astronaut
- To determine whether or not valid constraints and requirements had already been developed
- To become familiar with AMU ACS developments accomplished during previous programs

Two bibliographies provided sources of information:

- Honeywell Document RB-64-1, "Astronaut Maneuvering Unit Attitude Control System - A Report Bibliography", compiled by C. S. Rank
- Documentation Incorporated Bibliography No. Q528, "Selected Bibliography on Literature Survey on Attitude and Stabilizer Controls for Extra Vehicular Modules", by Robert Kassebaum, furnished by Documentation Incorporated at NASA direction

Subjects surveyed included:

- Function and task analysis
- ACS performance and operational requirements
- Orbital transfer (rendezvous) requirements
- Anthropometric data

FUNCTION AND TASK ANALYSIS

The major tasks of the astronaut operating in extra-vehicular space fall into three broad classes:

- Maintenance
- Transfer of men or material
- Emergency operations

The general type of motions engaged in by the astronaut during the performance of his duties outside the vehicle were investigated to determine the shifts of the centers of mass of the man-AMU system, the changes in the moments of inertia around the various body axes and the availability of body members for controller operation.

A function and task analysis (based on Reference II-1*) was undertaken to establish the movements of the major body parts. The extra-vehicular tasks, which emphasize the movements, are described in more detail below.

Maintenance

Maintenance is here conceived of as inspection, as often as necessary, of the external surface of the spacecraft or space station, and repair of whatever damage found. Damage from whatever source -- meteoroids, collision with another vehicle, skin stresses, etc. -- will require immediate attention, since the occurrence of even a small leak in the vehicle constitutes a hazard of potentially catastrophic proportions. Whether the astronaut is searching for the damaged area, or attending to its repair, he will need the capability of translating around the vehicle to the affected area, i. e., he will require both translational and rotational command capability. While at the work site, the astronaut will be required to manipulate tools appropriate to the repair task. This will involve transporting of tools and material, and will entail considerable hand

*References for this section are listed on Pages 31-33.

and arm mobility. It is not anticipated that the AMU will have to provide counteracting forces or moments during work activity. This seems to be a reasonable assumption since a large propulsion energy expenditure would be needed. Furthermore, effort is being placed on work task restraining harnesses or tethers as part of the total AMU development program.

Transfer Operations

One of the most important functions the astronaut can perform in extra-vehicular space operations is to assist in the rendezvous between two vehicles. The precision required for vehicle orientation and translation during docking maneuvers might be greatly facilitated by an extra-vehicular astronaut who can perform many of the tasks needed -- ranging from translation forward and towing of the target vehicle to locking of the two vehicles together.

Aside from an actual docking maneuver between two vehicles, an extra-vehicular astronaut may be required for the transfer of materials and cargo between vehicles -- tools, life support equipment, instruments, etc. Where transportation of a moderate amount of supplies between vehicles is called for, the extra-vehicular astronaut may be the most efficient, and in some cases the only, means of effecting the transfer.

The transportation of objects by carrying or towing by an AMU-equipped astronaut will require him to have the same capabilities as for maintenance -- rotation, translation, reaching, grasping, holding, etc. In addition, he will need visual capabilities permitting scanning and sighting operations preceding a rendezvous maneuver.

Emergency Operations

The possibility of an emergency arising is ever-present in the hostile environment of space. Depending upon the cause of the emergency (collision, explosion, leakage, etc.), and the nature of the crisis (blow-down, fire, etc.), the precise nature of the tasks confronting the astronaut will vary. In general, it is mandatory that the astronaut be prepared to undertake whatever necessary rescue or escape operations the occasion demands. Again, this will require the mobility, dexterity, visual capability, and rotational and translational control needed for maintenance and transportation tasks.

ORBITAL TRANSFER (RENDEZVOUS) REQUIREMENTS

The problem of rendezvous between an astronaut "flying" an AMU to a target in orbit was not, of itself, part of this study. Rendezvous does, however, impose requirements upon the ACS.

As one of the major functions of the ACS will be to position translational thrust jets in the proper direction, it is necessary to know how accurately the ACS must do this, based on rendezvous requirements. Another major function of the ACS will be to aid the astronaut in detecting velocity errors.

To determine these requirements, a literature search was conducted to see if previous work included accuracy requirements and error effects for the case of a short, low-relative velocity rendezvous. The following paragraphs describe the essence of the literature search and the numbers in parenthesis refer to the reference list on pages 31-33.

Thompson and Stapleford (II-2) and Hord (II-3) provide a comprehensive introduction to the problem of relative motion between an interceptor and target in orbit. Thompson and Stapleford include in their report a table which shows the initial conditions of papers studied during their literature search (Reference II-2, pages 22ff , and their comment, "Most other sources appear to assume initial conditions for the terminal rendezvous without justification or analysis." One exception to this statement was found in Reference II-4. Pages 99ff contain an error analysis of a free guidance scheme for a two-impulse field. A similar analysis, using values of range and initial relative velocity more appropriate to this study, is used later in Reference II-2 to help determine the accuracy requirements of the ACS.

Reference II-5 is a complete source for basic orbital data.

Reference II-6 gives a set of error propagation equations for rendezvous "established by analyzing the linearized central force equations" (Reference II-6, page 38). These equations, with some differences of sign, are derived in Reference II-7.

The Proceedings of the Manned Space Stations Symposium, April 1960, contains a number of articles on rendezvous guidance. Steinhoff (II-8) is especially interesting because of the wealth of numerical examples and estimates.

References II-9 through II-13 are studies of closed-loop rendezvous guidance systems. The initial conditions are, in general, assumed and little, if any, account is taken of sensor errors. Nearly all of the systems use an accurate measurement of the angular velocity at the line of sight. Reference II-14 is a study of closed-loop rendezvous guidance which contains some discussion of errors.

Griffin (II-1), Kasten (II-15) and Levin and Ward (II-16) simulated coplanar rendezvous. Not only did they assume initial coplanarity but also constrained the interceptor to the orbital plane of the target. Griffin concluded that thrust along the z-axis would suffice for correction of errors due to thrust misalignment. (In the actual case, however, it appears reasonable to expect errors in yaw at least as large as errors in pitch. Therefore, control along the y-axis must also be provided.)

Kasten (II-15) studied two modes of control. His study concludes that the one he calls "orthogonal thrust" is the better. In this mode, the pilot controlled simulated rendezvous with two levers. Deflecting one lever resulted in an acceleration along the line of sight proportional to lever displacement. Deflecting the second lever resulted in an acceleration at right angles to the line of sight in the orbital plane proportional to lever displacement. He concludes that "within the limitations of the simulation" short coplanar rendezvous can be made "repeatedly and reliably within minimum display and control equipment". (The possibility of yaw errors would require a third lever and judgment of yaw deviations.)

Levin and Ward (II-16) simulated rendezvous with displays that showed the relative position of the interceptor in the orbital plane and the relative velocity vector both on an oscilloscope and on dials. They found that over 50 people of widely varying backgrounds were able to complete a simulated rendezvous successfully. Admission of yaw errors would have required a third dimension in the scope presentation, two more dials and a third axis to the joy stick. The authors used the linearized equations of relative motion of Reference II-7.

Brissenden, et al (Reference II-17) show the derivation of the equations required for analog simulation of rendezvous. While careful attention is paid to some rather subtle effects such as tidal acceleration, other effects such as integrator drift, are not discussed. Since the report does not show the complete simulation diagram, one cannot tell how all these difficulties were dealt with.

During the Space Rendezvous, Rescue, and Recovery Symposium held at Eglin Air Force Base in 1963, the need was stressed for "real" pilot-controlled rendezvous (Reference II-18). This approach was highlighted by Novak, Air Force Institute of Technology, Wright Patterson Air Force Base, Ohio, in Reference II-18 in a description of a method whereby a man could travel about a mile in space in going from one orbiting satellite to another. He reported that the technique found most suitable, through theoretical investigation, is the fixed-line-of-sight maneuver. This concept utilized the apparent drift of the stars. Novak claims that the technique approaches the ideal two-impulse maneuver in efficiency.

To summarize the state of the art from the point of view of this study:

1. Some extensive and accurate general work has been done.

2. There is considerable loss of generality in the studies of applications. Nearly all of the application studies are narrowly restricted as to initial conditions, sensor accuracy, and the effects of errors introduced by analytical simplification.

3. There is a large body of work on closed-loop rendezvous. Many of the studies assume perfect sensors or various analytical simplifications without investigating the effect of these assumptions.

4. All of the studies which might have borne upon the determination of required accuracies of the ACS have constrained one major source of error to zero. In all cases the deviation of a target from some reference line has been made available to the pilot. None of the studies has considered the effect of errors and biases in this information. None of the references has mentioned the effect of attitude limit cycling on the determination of line-of-sight angular rates. All of these references reach the conclusion that pilot-controlled rendezvous presents little problem. It is difficult to share this certainty in the AMU six-degree-of-freedom case, which will undoubtedly depend on ocular sensing of errors.

ANTHROPOMETRIC DATA

It was necessary to collect anthropometric data on the typical astronaut for two reasons:

- To ascertain whether the pressure suit would interfere with the astronaut's performance of tasks required of him in extra-vehicular space

- To obtain data on the mass of the human body to facilitate dynamic analysis of the ACS

Effect of Pressure Suit on Body Measures

Measures of the static sizes and the range of movements of the suited astronaut are important to the AMU ACS design for three reasons:

- Static sizes and the range of such gross body movements as bending, kneeling, and stretching will define maximum variation in center of mass and inertias of the suited astronaut with backpack.

- The range of fine body movements, such as reaching, grasping, and twisting, will determine the tasks that the astronaut is able to perform.

- Mobility of the limbs of the astronaut may determine location and operating characteristics of the ACS controller.

Properties of Pressure Suits -- Preliminary investigations of the properties of pressure suits currently under consideration for space travel show some inconsistency between suits made by different manufacturers. Differences between them when they are inflated make exact comparison difficult. Furthermore, this study did not cover the properties of a hard suit. Development is being conducted within the aerospace industry and a significant degree of improved mobility is anticipated. This can be investigated at a later stage of its development.

Some generalizations, however, are possible with regard to pressure suits:

- There is a neutral arm position (arms extended forward, elbows slightly bent) that is a function of suit design. This neutral position could be altered, if desired, in the design stages of suit construction.

- Arm movement excursions away from the neutral position can be made only if the wearer applies considerable force.

- A pressurized suit limits the range of arm, elbow, hand, and finger movements.

- Control placement and manipulation are of the utmost importance, since most limb movements are difficult to perform and impossible to maintain.

Mobility of Operator Wearing Pressure Suit -- The degradation of movement and manipulation abilities of the operator can only be roughly estimated. Results of an in-house study conducted using a typical space suit are summarized briefly below. These results were obtained in a one-g gravity field.

Touching Toes -- Mobility at the waist and hip are considerably restrained. Hands could be lowered to about the level of the knee.

Raising Leg -- Restraint on the flexion of hip and knee confined the leg lift to about one-third its normal (unsuited) range.

Kneeling -- Severe pressure points behind the knees and uneven pressures on the body make maintenance of this position for any length of time highly undesirable. An improvement in the design of pressure suits may remove this difficulty.

Lying Down -- This could not be accomplished without assistance, but has no analogy to a change of orientation in a weightless condition.

Reach measurements were made using simulation equipment. Suited and pressurized, a subject could reach a maximum distance of 22 inches and could describe a roughly circular arc 17 inches in diameter directly in front. In shirtsleeves, the corresponding figures are 28 inches and 39 inches, respectively.

The most detailed study reported was conducted by Springer and Bommarito (II-19). The mobility of several test subjects was investigated using four different suits at low pressure levels. (The suits investigated were the B. F. Goodrich Mk. II and Mk. IV and the Arrowhead Rubber AX 6-10 and AX9. Measurements were made with the suits at pressures of 0, 3.0, 3.5, and 3.8 psig, respectively.) In general, the measures of maximum arm deflection agreed well with other studies.

A more extensive study was conducted by Belasco (II-20) using a Mk. IV suit at 1.0 psig. (The reason for conducting tests at 1.0 instead of 3.5 psi was to obtain "simulation of anticipated increases in mobility through reduction in suit pressure".) Static measurements of the standing subject are presented in Table 1. A series of gross body movements was made and classified as "easy to perform", "difficult to perform", or "impossible to perform". Results are shown in Table 2.

A series of limb movements was made to determine the mobility limits of the pressurized suit. These results are summarized in Table 3 and compared with corresponding movements made by an unsuited subject. [The data for the latter was taken from Dempster(II-21).]

Table 1. Crew Transfer Study - Static Anthropometric Data

Item	Inches
Standing Position	
Height	70-1/2
Eye	65-1/8
Shoulder	57-3/4
Knuckle	32
Arm span	68-7/8
Shoulder breadth	21-1/4
Extended arm	31-13/16
Chest depth	Not obtained
Chest depth plus back pack	19-1/16
Back-pack depth	Not obtained
Seated Position	
Seated height (from ref. point)	36-5/16
Shoulder height	24-3/4
Elbow	9
Knee	23-3/4
Buttock-knee	24-5/8
Hip	13-3/4

Table 2. Functional Gross Body Movements at 1 psig
(Reprinted from Reference II-20)

Easy to Perform

Fall to prone position from standing position on a mat.

Roll from supine to prone position

Raise from a prone position to hands and knees.

Crawl forward 6 feet.

Crawl backward 6 feet.

Execute a 360-degree turn in place on hands and knees.

From hands and knees, raise to sitting position with feet extended with no assistance. (No assistance required)

From hands and knees, raise to sitting position with feet extended with assistance; namely, the use of a wall chair or physical support. (No assistance required)

Raise from hands and knees to an upright position with the use of wall chair or other physical support.

From the upright position, lower to hands and knees without help.

From the upright position, lower to hands and knees with the use of wall chair or other physical support (No assistance required)

From the upright position, lower to a deep squat.

Raise from the deep squat to the upright position (note: with or without assistance). (No assistance required)

Walk 50 feet on level grade at slow speed, turn 180 degrees and return.

Walk 50 feet at maximum speed straight away, if possible.

Walk sideways by side-stepping at least 5 feet.

Walk backwards 5 feet.

Walk up a standard staircase with 8-inch risers for at least four steps; turn on the steps and walk down with or without handrails.

Standing broad-jump. Distance 38½ in. .

Three-step jump. Distance 38½ in. .

Jump down from a 1-foot platform.

Difficult to Perform

Roll from prone to supine position wearing back pack.

Side-step 4 feet to the right in a hands-and-knees position.

Side-step 4 feet to the left in a hands-and- knees position.

Raise from hands and knees to an upright position with no assistance (no assistance required)

Climb a vertical ladder with 8-inch risers and flat rungs. Climb up four steps and down four steps.

Raise man with a simulated backpack and/or umbilical by the shoulders and drag 10 feet in a straight line.

Impossible to Perform

Raise man clear of the floor (approximately equal in weight to the subject) and carry for a distance of at least 6 feet.

Table 3. Comparison of Body Movements Between Suited and Unsuited Subjects

Movement	Suited (Ref. II-20)	Unsuited (Ref. II-21)
Maximum lateral arm movement	0° (down) to 90°	
Maximum fore-and-aft arm movements	-30° to +135°	-61° to +188°
Maximum hip bending (touching toes)	+60°	
Maximum knee bend (crouch)	130°	159°
Maximum front overhead reach	8 inches above top of helmet	
Maximum leg raise	45°	
Maximum leg (knee) bend (standing)	90°	113°
Maximum frontal arm reach	22 inches in front of shoulder	

It is anticipated that the extra-vehicular astronaut will be required to exercise mobility of the arms and hands, in preference to other body members, in the performance of his tasks. For this reason, data relating to arm and hand motion limits was abstracted from the foregoing tables, and are presented pictorially in Figure 1. From this data, it can be concluded that the suited astronaut is capable of the degree of arm mobility and hand dexterity required for performance of his extra-vehicular tasks as set forth earlier in this section under "Function and Task Analysis."

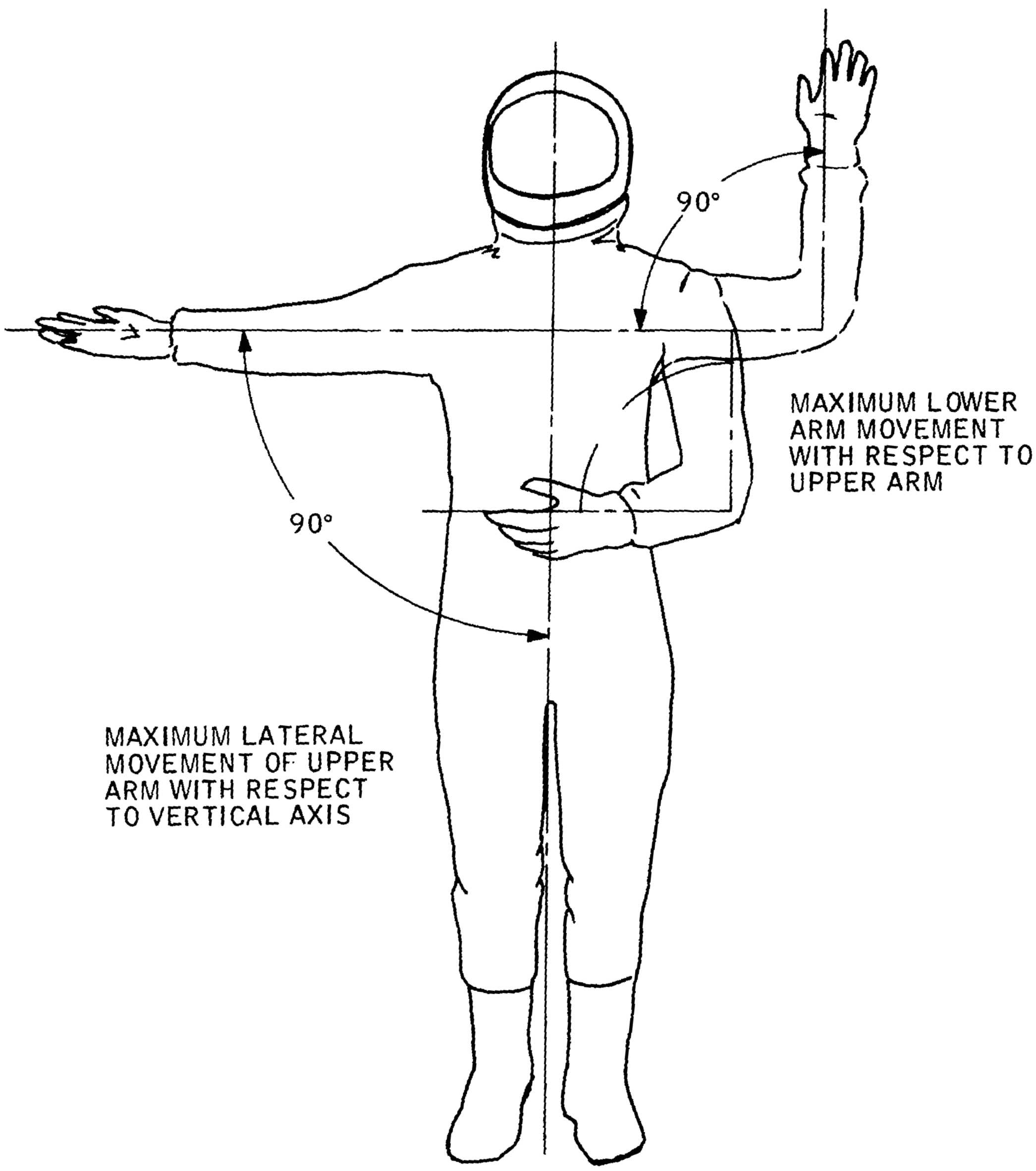


Figure 1. Arm Movement Limits

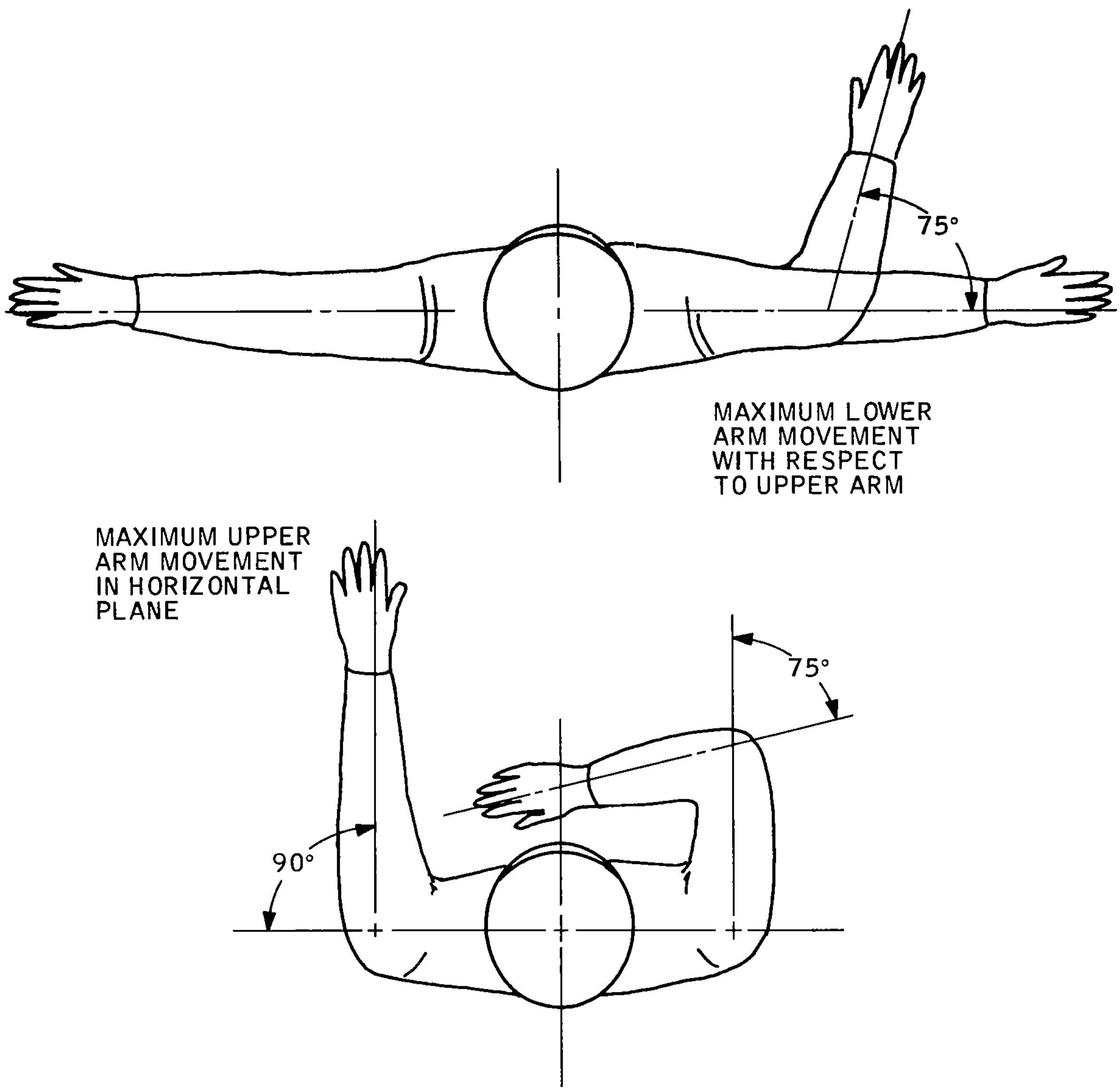
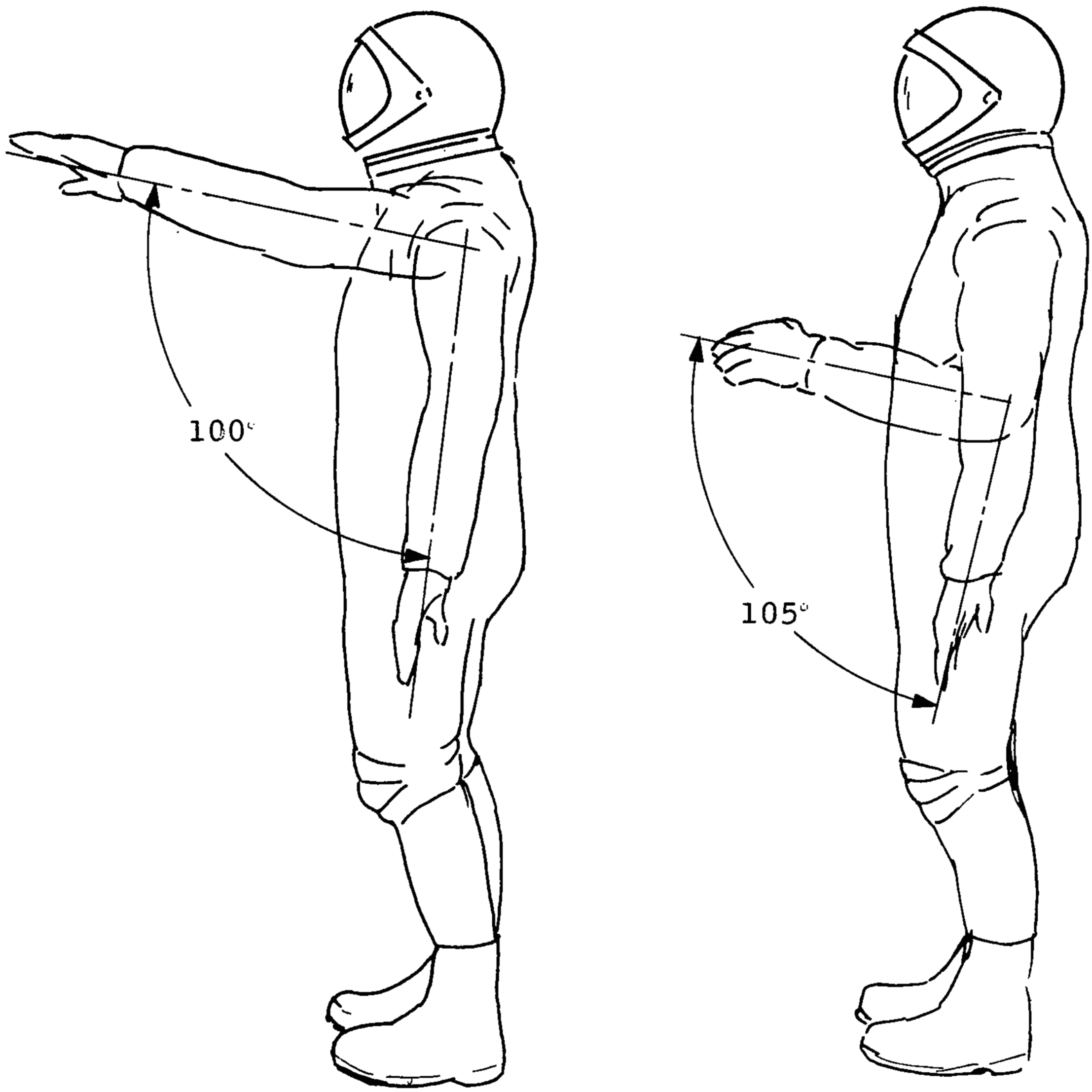


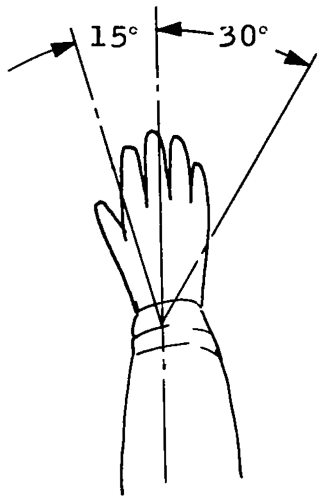
Figure 1. Arm Movement Limits (Continued)



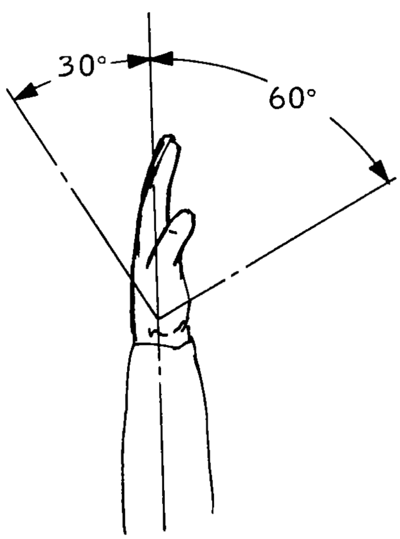
MAXIMUM FORE-AND-AFT MOVEMENT OF UPPER ARM WITH RESPECT TO VERTICAL AXIS

MAXIMUM LOWER ARM MOVEMENT WITH RESPECT TO UPPER ARM

Figure 1. Arm Movement Limits (Continued)



WRIST LIMITS



ROTATIONAL LIMITS:
RT HAND CLOCKWISE: 60°
RT HAND COUNTER-CLOCKWISE: 30°

Figure 1. Arm Movement Limits (Continued)

Body Coordinates, Masses, and Moments of Inertia

For use in the AMU-ACS simulations, it was necessary to know the location of the center of mass, location of the principal axes, and principal moments of inertia for each posture likely to be adopted in flight. Data from several sources were found in Whitsett (Reference II-22). Table V of this reference gives the weight, density, length and centroid location of each body segment. Table VI gives the coordinates of the body segment hinge points and mass centers. Table VII gives the moments of inertia of the mass segments in two postures.

The data required for the Honeywell AMU-ACS study program was generated from these tables and is summarized in Section III.

ACS PERFORMANCE AND OPERATIONAL REQUIREMENTS

The attitude control system for the astronaut maneuvering unit is a particular application within the broad category of satellite and space vehicles. Thus, a number of documents within that basic category were reviewed first. Second, several documents concerning AMU developments were evaluated. The background established as a result of this survey was needed to help establish the specific design requirements and control schemes to be considered for the AMU ACS. Limitations imposed were that consideration was restricted to on-off control system schemes and components which have been found useful to such control systems.

Satellite and Space Vehicle Control

Several general references were found which concern the control of satellites and space vehicles. Application to the AMU of many of the mechanization methods discussed does not appear to be advantageous.

Haeussermann (II-23) covers information published prior to November 1961. Included in this reference is a list of 100 pertinent references. General characteristics and performance are discussed as follows:

Space Vehicles With Attitude Control Systems -- Haeussermann notes that only very limited information has been published about attitude control systems which have seen actual use. ACS configurations are discussed briefly (and the reader is referred to the listed source articles) for Mercury, Discoverer, a recoverable space probe, Orbiting Astronomical Observatory, Ranger, and the 24-hour Communication Satellite.

To obtain precise attitude orientation or a fast settling time capability, several sensing methods are available:

- Sensors for extended objects such as infrared or visible radiation seekers (horizon, planetary, and sun seeker)

- Sensors for point sources such as star seekers or trackers

For the AMU application, horizon and/or target trackers may be required to adequately solve the guidance problem. These devices are available; they have been used in space applications. Extensive background material is documented with respect to detector materials, filters and lenses, temperature requirements, and scanning techniques.

Because many applications require inertial reference information, special schemes and specific developments have been started. In particular, need exists for increased gyro life (increased reliability), greater accuracies, reduced power requirements, and automatic checkout. It is Haeussermann's opinion that before rate gyros can be effectively used for stabilization, required power must be reduced and sensitivity must be increased. Until then, dynamic stabilization must be based on compensation networks acting on the attitude error signal.

Schemes for providing the link between the sensors and actuation means are described also. For simpler systems, these schemes are normally mechanized with an analog computer - amplifier approach. For sophisticated systems which perform complicated guidance computation, a digital computer is required which probably can also perform the attitude control computation.

Several actuating schemes are available. The specific application determines which one or which combination should be used. Various types of mass expulsion devices are described as well as rotary reaction systems. Although reaction jet systems must be designed for the greatest thrust needed, means are available, such as pulse-rate and pulse-width modulation, to effect precise control without excessive fuel consumption.

Rotary reaction wheels or spheres must be restricted to control of oscillatory or random sign errors to avoid saturation. If wheel speeds are high, coupling is significant because of the gyroscopic effects. Gyroscopic torquing has also been investigated. Coupling again is a problem; decoupling must be obtained in order to establish the best available performance. Normally any rotary reaction scheme must be restricted also to low torques, thus providing very accurate control capability.

Future Development -- Haeussermann views the argument of pilot capability versus automatic control as one of the most controversial items. He also views any effort to give the astronaut duties similar to those given an airplane pilot as being a serious risk. His reasoning is that neither training in the actual vehicle nor completely authentic environments during simulation training can be provided. On the other hand, automatic control equipment normally can be tested in entirety prior to actual use.

In addition to Haeussermann's survey, a comprehensive handbook (II-24) and an annotated bibliography (II-25) are available. The handbook was prepared by the Systems Corporation of America under ASD contract (R. E. Roberson, editor) and published in three volumes. Special characteristics, performance requirements, and supporting data for concept and equipment are discussed in Volumes I and II, and given in a classified category in Volume III.

Analytical Techniques

Various analytical techniques have been developed for application to a specific problem or class of on-off control system problems. These techniques are applicable, in varying degrees, to the AMU ACS.

Reference II-26 includes the frequently used phase-plane technique for definition of a space vehicle attitude control system. Nonlinear effects of hysteresis, dead zone, and thrust time delays upon limit cycle characteristics are included. System settling time and fuel consumption are optimized using trial and error. Additional effects on the limit cycle for pulse frequency and pulse width modulation of a fixed thrust magnitude are evaluated in Reference II-27. Effects of external torques, both stabilizing and destabilizing, are included.

Design charts for determining system parameter values are presented in Reference II-28 for a system which uses angular position and rate feedback. Effects of time delays, rise and decay times, and dead zone are included. Reference II-29 emphasizes the practical design aspects. The requirement of having a high torque capability as well as very efficient operation with no disturbances present is imposed. Through utilization of existing nonlinearities with logically controlled pulsed reaction jets, the design goal is realized.

Frequently, in order to obtain the desired limit-cycle characteristics, rate gyros must be used rather than networks which operate on the attitude error signal. A method which extends the performance capability of systems without rate gyros is described in Reference II-30. It is based upon the measurement of the thrust "on" time to give a "pseudo rate".

Other analysis techniques also are appropriate. For the class of problems wherein vehicle angular acceleration is proportional to the applied torque and when system transients decay prior to control torque application, a "rate diagram" method can be used. As defined in Reference II-31, the rate diagram is a plot of vehicle angular rate at control torque removal versus the rate at torque application.

References II-26 through II-31 concern analysis of simple second-order systems, although rather complex nonlinearities may be included. Reference II-32 utilizes a technique -- that of describing functions -- for handling higher-order systems. The advantage is that linear system analysis methods may be applied. However, assumptions implicit in the use of describing functions to represent nonlinearities impose severe restrictions on allowable system error signal characteristics.

Two significant state-of-the-art situations are demonstrated by the above references:

- The practical approach to synthesis of control systems is based on analysis techniques with very limited capabilities.

- The applicable technique and approach used depend upon the problem to be solved.

Reference II-33 was written in an attempt to bring some order to the synthesis of a control system for a specific vehicle with a specific mission. In particular, the purpose was:

- "To establish the present level of development of the analytical techniques for the study of nonlinear control systems."

- "To provide insight regarding the application of the existing analysis techniques to the practical design problems of space vehicles attitude control systems."

Furthermore, it is pointed out in Reference II-33 that although it would be very desirable to have a direct means of synthesis, the currently available methods are very restricted in application. Therefore, the determination of the "best" or "optimum" design must be found through intuitive reasoning, experience, and "cut and try". Analysis techniques must be selected judiciously, therefore, for a specific problem, in order to optimize the design.

It would appear that none of the "paper and pencil" techniques lend the same confidence to the design that simulation on an analog computer does. Thus, simulation and/or operation of breadboard or prototype systems with a simulated vehicle becomes a necessary part of the analysis rather than serving only to confirm the design.

Reliability

Reliability considerations may be broken into two major areas:

1. Defining the required subsystem reliability. This takes the form of specifying a "fair share" number which, along with the "fair share" reliability of all other subsystems, gives the system reliability needed to obtain the desired system effectiveness. Techniques for accomplishing this task in an organized manner are available (II-34).

2. Determining a subsystem design which meets the defined subsystem reliability requirements. Component reliability data, computational techniques, and reliable design concepts are available which permit a relatively straightforward analysis. Again, intuition, experience, and "cut and try" must substitute for synthesis, as in the case of system design. Reference II-35 describes a study which illustrates all factors involved in designing for a specific function with a specified reliability.

Astronaut Maneuvering Units

Development of an attitude control system for an AMU has progressed to the developmental model stage. Tests have been conducted under simulated conditions using an air-supported platform. Additional tests have been conducted inside a KC-135 aircraft while in a zero-g trajectory. Feasibility of the complete unit was considered in Reference II-1. Specifically it was a study of:

- "The requirements and capabilities expected of astronauts engaged in space operations."

- "The development of a small self-contained pack utilizing propulsion, stabilization and control, and life support systems to afford the orbital worker complete support while performing space maintenance functions."

With respect to the ACS, Reference II-1 makes the following major points:

- In order to realize an optical guidance scheme for orbit transfer, the astronaut probably will have to be precessed consistent with his orbit speed. This requirement results because relative line-of-sight angular rate in pitch must reflect target movement only.

- Angular rotation should be limited to 5 to 10 rpm in pitch, 4 rpm in roll, and 8 rpm in yaw, on the basis of induced physiological effects. Although these rate limits will undoubtedly be lowered if coupled movements are considered, no conclusions are given.

- Automatic stabilization is a firm requirement if pulse-type reaction control is used and only visual cues are used for attitude orientation.

- Recommended rotational rates and translational acceleration and velocities are given.

- Finger stick control located eight inches in front of the chest at elbow height is recommended.

- Specific control and stabilization requirements are given. Of note are the following: Attitude stabilization accuracy of ± 10 degrees, rate command capability with unlimited angular freedom with the maximum rate command equal to 0.5 radian per second.

- Switching logic is derived for a five-degree-of-freedom reaction jet control system.

Results of the Reference II-1 work have been extended to the construction and test of an experimental maneuvering unit.

Reference II-36 describes the tests performed (using a developmental model defined in Reference II-1) during a simulated zero-g environment in an Air Force KC-135 aircraft. Control was provided with attitude rate stabilization, attitude rate command, and attitude and translational manual control modes. It was concluded that 10 pounds of thrust for up and down maneuvers and 20 pounds fore and aft can be handled easily. It was the opinion of the pilots that the fore and aft thrust could be increased to 30 pounds. It was suggested that a reaction-jet pulse-width modulation scheme would be desirable to reduce oscillations. Although no pressure suit was used, difficulty was experienced in using the controller, primarily because of the speed with which successive control action had to be made in order to execute the "flight plan" in the very limited zero-g time available.

A history of development by Bell Aerosystems Company of the zero-g belt concept is presented in Reference II-37. Results of tests of a developmental model utilizing an air-bearing platform and flight test in an Air Force C-131 aircraft are given. Background for the zero-g belt development is the work done on the small rocket lift device (SRLD) for free flight by a man in a one-g environment. Difficulties were experienced with uncontrollable lateral oscillation. A need for thrust vector control also was established. Means of providing damping were studied.

Automatic stabilization for the zero-g belt is rejected in Reference II-37 as a result of the following considerations:

- "Experience with the SRLD provided conclusive evidence that under conditions of one-g environment, a man can manually stabilize his attitude and control his flight path."
- "Air Force personnel who at that time had the most extensive experience with the operation of man-propulsion systems under zero gravity, were of the opinion that manual stabilization and control might be feasible."
- "Until an adequate propulsion system was made available to evaluate the learning factor and to define the parameters and degree of control and stability required, a final decision for automatic versus manual stabilization and control could not be made."

A "flexible man" was defined and included in the analytical studies. A belt design was developed which used direct mechanical reaction jet valve control in response to manual control inputs. Major conclusions reached with respect to ACS design as a result of the test work are as follows:

- "A two-hand controller is not desirable. It has been determined that a single-hand controller is necessary so that the second hand is free for other functions and to assure an equal thrust application on both sides to prevent unintentional rotation."

- "Throttleable thrust is required. The operator should be able to vary the thrust output over the entire range of thrusts possible. It is important that the thrust utilized for rotational control be optimum for each axis because of the different moments of inertia present in each axis."

- "Because of the short exposure to zero-g during any one parabola and because of the disturbances induced by turbulence and imperfect trajectories, it was not possible to assess man's capability to stabilize himself without some augmentation."

The functions of the ACS while the astronaut is in the immediate vicinity of the target vehicle or at a work station are in part clarified by References II-38 and II-39. It apparently can be anticipated that through use of restraints no moments will have to be produced by the ACS to counteract moments induced by the work task. It is also probable that tether lines will be available to permit the astronaut to "let go" of his vehicle without complete dependence upon an ACS or translational thrust system for assistance in his return.

The present state of the art is summarized below:

- Controlled "flight" is feasible in a zero-g environment.

- Automatic stabilization is probably necessary.

- Angular velocity limits have been established.

- Jet thrust levels for translation have been approximately established.

- No controller reported in the references is considered satisfactory; at least one hand must be free at all times.

- The ACS should not have to provide counteracting moments in the performance of most work tasks (except in transporting tools or material).

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SECTION III
GENERAL CONSIDERATIONS

ASSUMPTIONS AND CONSTRAINTS

The AMU-ACS study program had as its purpose the design of an attitude control system for astronaut maneuvering units. It was assumed that the astronaut's mission was rendezvous with another object in orbit (less than 5 nautical miles distant), performing work tasks at the target, and returning to the original vehicle. The ACS requirements were established consistent with the assumed mission and the following assumed constraints:

- The astronaut would wear a space style pressure suit.
- An AMU containing life support, communications, power, attitude control equipment, and the associated controller would be worn by the astronaut as a backpack.
- Size, weight, power consumption and thermal dissipation must be kept to the minimum consistent with mission performance.
- A mode should be provided in which the gyros are "caged", with no jet actuation permitted.
- The number of visual displays should be kept to a minimum.
- Some sort of emergency attitude control should be provided.
- Hand actuation requirements should be minimized.

- The astronaut's visibility shall not be obstructed.
- Mass expellant jets would be used for translational and angular accelerations.
- All heat dissipated by attitude control packages would be transferred by conduction to the AMU and dissipated by radiation.

REACTION JET CHARACTERISTICS

Certain characteristics of reaction jets, typical of such systems at the start of the program, were assumed. These are detailed in Paragraph 5. 2 of Section I, **Appendix A of this report.**

ACS REQUIREMENTS FOR RENDEZVOUS

The rendezvous guidance scheme imposes requirements upon the ACS. For one reason or another, schemes found in the literature are unrealistic or impractical (see Section II, Orbital Transfer Requirements, of this volume) To establish the requirements for an ACS for the AMU, it was necessary to select a guidance scheme and consider the requirements it imposes on attitude control.

Consideration of relative motion between two objects in orbit without simplification requires step-by-step integration of the equations of motion. If this integration were done on a computer, the analyst could not intervene often enough to study the effect of various schemes. If the work were done by hand, not enough schemes could be considered since the selection of a reasonable guidance scheme is incidental to the performance of the contract. Consequently, a guidance scheme was selected by assuming (1) that no guidance scheme is suitable which will not solve the field-free case and (2) that the requirements imposed on attitude control by a field-free guidance system are similar to those imposed by a system which solves the actual problem. Note that some guidance routines which solve the field-free case will not solve the unsimplified case.

The guidance scheme selected on the basis of these assumptions is described below:

1. The spacecraft will establish the initial conditions and measure range, range rate, and cross-range velocities. For this scheme the cross-range velocity must be less than 3 fps to avoid large initial corrections.

2. The astronaut, using his knowledge of these initial conditions, thrusts toward the target to attain a predetermined range rate (or relative velocity) v.

3. Due to thrust alignment errors (and residual cross-range velocity) there will be some error angle E between the line-of-sight and the relative velocity. This angle is measured in the plane of the target, interceptor, and relative velocity. This plane, shown in Figures 2 and 3, may change after each corrective thrust.

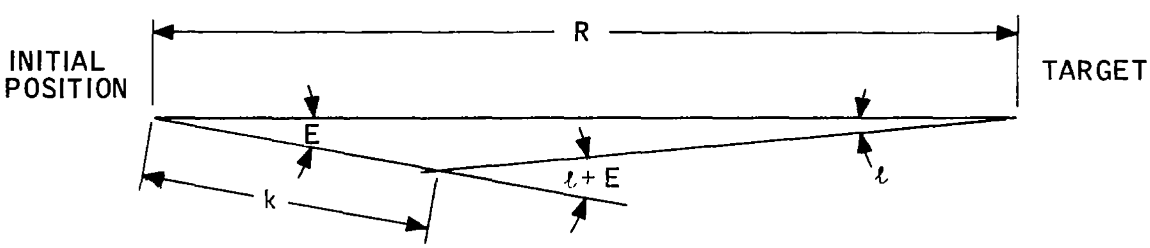

Figure 2. Rendezvous Geometry

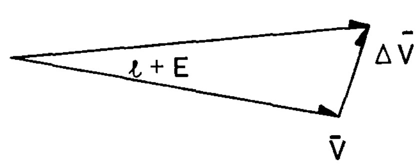

Figure 3. Vector Diagram

4. Immediately after thrust, the astronaut will note the bearing of the target. When the bearing changes by angle, ℓ (the threshold), the Law of Sines gives $\sin(\ell + E) = \sin \ell / \left|\frac{k}{R}\right|$. Since the astronaut knows R and v and can measure the time from start until the bearing changes, he can find k as follows:

   Let $T = \frac{R}{v}$ and t_1 = time from start to bearing change

   $$\frac{t_1}{T} = \frac{k}{R} \quad ; \quad k = \frac{Rt_1}{T} = \frac{Rt_1}{R/v} = vt_1$$

   Using this value of k he can find $(\ell + E)$ from $\sin(\ell + E) = \frac{\sin \ell}{k/R}$

5. The vector diagram of Figure 3 shows that $\Delta v = v \tan(\ell + E)$. Since for angles up to 200 milliradians, $\tan \theta$ differs from $\sin \theta$ by less than 5 per cent and all the angles are in this range,

   $$\Delta v \doteq \frac{v\ell}{k/R}$$

6. In order to complete the solution, steps 2 through 5 are iterated, with R replaced by (R - k), as many times as necessary.

7. When the astronaut sees that he is approaching the target, he will apply braking thrust.

The consensus of investigators is that the astronaut will be able to judge distance accurately at 50 to 100 feet. It is assumed that he will be too busy during retro-thrust to make normal corrections to the guidance system in the last 50 feet. It has also been assumed that he can adjust for errors of 2 feet by arm reach. A 2-foot error subtends an angle of 40 mr at 50 feet. This angle is the upper limit for the threshold.

Figure 3 shows that each correction results in an increase in magnitude of the relative velocity (Δv rel). In order that the impulse required at retrothrust be fairly predictable, the condition is imposed that the final relative velocity be within about 10 per cent of its original value. In several cases calculated by hand, 5000-foot rendezvous required four corrections. Extrapolating the result to 30,000 feet (the maximum suggested in the literature), 24 corrections would be required.

$$\Delta v \text{ rel} = \sqrt{v^2 + \Delta \bar{v}^2} - v = \sqrt{v^2 [1 + (\Delta v/v)^2]} - v = v\left[\sqrt{1 + (\Delta v/v)^2} - 1\right]$$

Now $\sqrt{1 + (\Delta v/v)^2} = 1 + 1/2\, (\Delta v/v)^2 - (1/2)(1/2)(\Delta v/v)^4 + \text{etc.}$

$$\doteq 1 + 1/2\, (\Delta v/v)^2$$

If $\Delta v/v < 0.2$, the error incurred by truncation is less than 2×10^{-4}.

$$v \text{ rel} \doteq v[1 + 1/2(\Delta v/v)^2 - 1] = v[1/2(\Delta v/v)^2]$$

As a fraction of v,

$$\Delta v \text{ rel}/v = 1/2(\Delta v/v)^2$$

Rather than a calculation involving a fraction derived from applying a recursion formula 24 times, it will be assumed that each correction adds the same increment of magnitude to the relative velocity. This will overestimate the effect of the corrections or underestimate the maximum Δv. The procedure is conservative in that sense.

$$24[1/2(\Delta v/v)^2] = 0.1$$

$$(\Delta v/v)^2 = 0.00834$$

Then $\Delta v/v = 0.0912$, which for an 80-mr error requires a threshold of 11 mr and for a 70-mr error requires a threshold of 22 mr (see Figure 4). Note that the required threshold is extremely sensitive to assumed error magnitude in this range when $\Delta v/v$ is held constant.

Several field-free rendezvous were run using different nominal thresholds with errors in the actual threshold. The range and initial error were held constant. Total $\Delta v/v$ and error at 50 feet were calculated. The following preliminary conclusions were reached:

1. The nominal threshold should be 20 mr. Field-free rendezvous were satisfactory at this level. If the required threshold were reduced appreciably, attitude control complexity would be increased considerably with negligible savings in propellant consumption. If the required threshold were increased significantly, it would be much less likely that the error at 50-foot range would be below 40 mr.

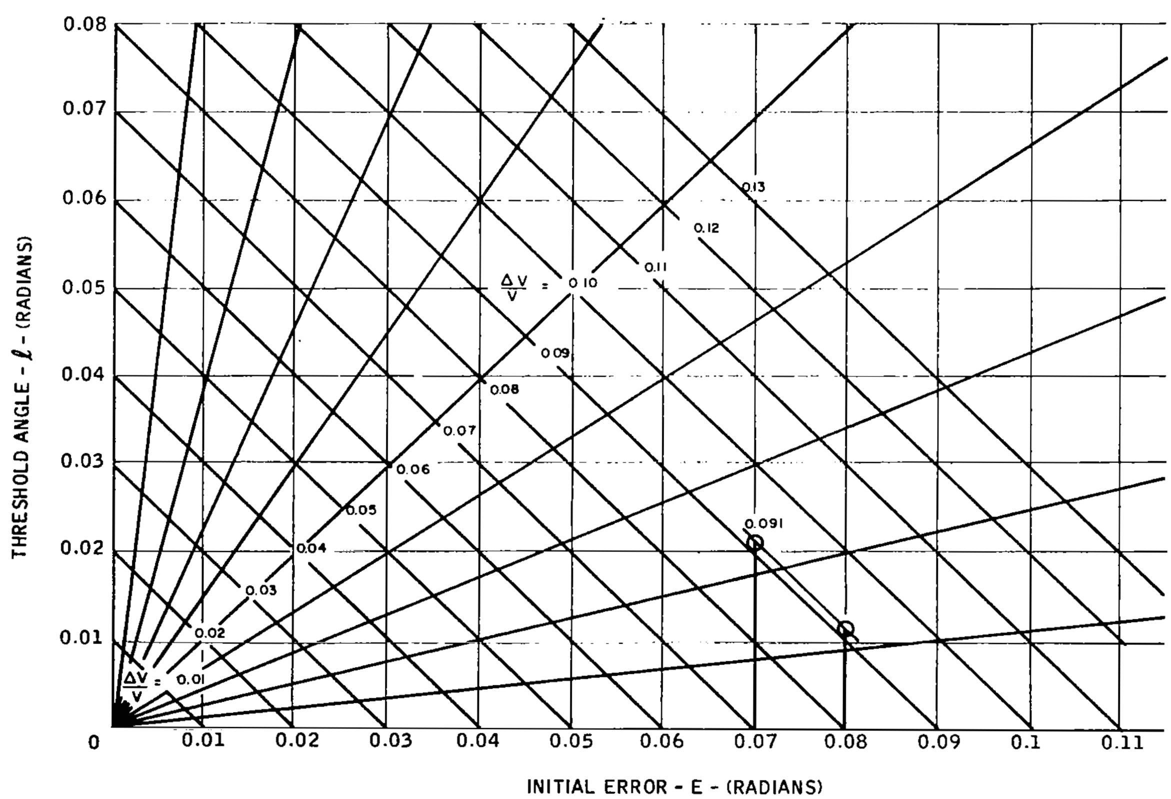

Figure 4. Correction Functions for AMU Rendezvous

2. To determine the attitude control requirement, it is necessary to determine the contribution of the optical system to threshold. Recent optical devices (telescopic rifle sights, for example) have been able to hold threshold plus alignment errors to considerably less than 0.3 mr (1 inch at 100 yards). It appears then that the optical contribution to threshold may be neglected and 20 mr should be imposed as a requirement on the attitude control system.

3. If the actual threshold is less than nominal, the propellant consumption is excessive and in some cases no reduction of the initial error takes place; instead the error is overcorrected. Then an equal but opposite impulse is called for which again overcorrects and restores the error to its original value, and this oscillation continues.

4. The guidance problem is renewed after each correction. During corrections, principal function of attitude control is to assure that the corrections are in the proper direction. The velocity correction increment fed into axes other than the one desired can be held to less than 10 percent if attitude excursions during velocity corrections are held to 100 mr. If duration of the velocity correction occupies an appreciable part of a limit cycle, the velocity correction coupled into other axes will be less than 10 percent.

ENVIRONMENTAL REQUIREMENTS

The environmental requirements were selected to ensure:

1. Environmental and structural suitability during the AMU mission

2. Environmental and structural suitability during a typical launch

3. Prevention of damage from short-term exposure to the elements and long-term protected storage at the launch site

4. Structural integrity after a severe shock

A maximum average thermal input from the ACS to the AMU of 25 watts per square foot of attachment plate was selected in order to keep base plate temperatures below 100°F. Proper operation is required at reduced pressure and after exposure to ambient temperatures of 160°F and -60°F.

In order to ensure suitability during a typical launch, it was specified that the equipment pass the vibration and acoustic noise requirements outlined in McDonnell Aircraft Corporation Report 8610 (submitted under Contract NAS9-170) entitled "Gemini Spacecraft Environmental Criteria Specification". Structural integrity after a severe shock is ensured by specifying the shock test that is specified in the above report.

Protection against handling and storage damage at the launch site is ensured by specifying that the equipment pass salt atmosphere, sand and dust, fungus, and humidity tests from the above McDonnell report.

During the determination of the environmental requirements for the electronics and sensors, the radiation dose in typical, predicted AMU orbits was examined. Because electronic devices are so much less sensitive to radiation than the astronaut, no environmental requirement was imposed.

Radiation potentially dangerous to the men and electronics carried aboard an orbiting satellite can be divided into three categories:

1. Primary galactic cosmic radiation

2. The geomagnetically trapped radiation

3. The high intensity radiation from large solar flares

The intensities and energy spectra of the components in the first type of radiation have been carefully measured and are found to be consistent and predictable -- with the intensities varying by a factor of two over the 11-year solar cycle (Reference III-1). The topography of the inner belt of geomagnetically trapped radiation has been recently determined by McIlwain (Reference III-2).

The third type of radiation -- large solar flares -- is not so predictable. In the last solar cycle six solar flares occurred, producing radiation of a dangerous intensity level. All six occurred within a three-year period about the maximum solar activity level in 1958; however, the specific occurrence of a large solar flare event is not yet predictable.

Table 4 has been compiled to illustrate the general level of radiation dose rate to be expected for circular orbits inclined at 30 degrees and not surpassing 10,000 miles in altitude.

Table 4. Expected Radiation Dose Rates for Low-Altitude, Low-Latitude Orbit

Type of Radiation	Altitude (mi)	Dosage Rate (r/day)	No. of Days for 20 r*	No. of Days for 10^5 r**	Shielding (gm/cm^2)
Primary Galactic Cosmic Radiation	25-400	2×10^{-3} (Ref. III-3)	10^4	5×10^7	0
Geomagnetically Trapped Radiation in Inner Belt	400-10,000	3 (Ref. III-4)	7	3×10^4	0.43
Solar Flare Radiation	>25	200 (Ref. III-5)	0.1	500	1.0

*Limit dose tolerable to man (Reference III-6).

**Dose at which most sensitive semiconductors become affected.

The values given in Table 4 for galactic primary cosmic radiation refer to a latitude of 30 degrees -- as a vehicle travels toward the equator, the dose will be less due to the shielding of the earth's magnetic field. Shielding will not be effective in reducing the dose rate received from cosmic radiation because of the penetrating quality of these high-energy particles. In fact, the secondary radiation produced in any reasonable shielding by a primary cosmic ray would be at least as harmful as the original particle itself.

Geomagnetically trapped radiation values given in Table 4 are typical for the inner belt which occupies the region 400 to 10,000 miles above the earth's surface and at ±30 degrees of latitude. Values were calculated for a shielding at 0.43 gm/cm^2 and thus are applicable to the Gemini capsule whose 0.030-inch of titanium represents 0.35 gm/cm^2 of shielding.

Solar flare radiation intensities shown in Table 4 are only a very crude estimate based upon the large solar flares observed in the past. Values quoted are for 1 gm/cm^2 of shielding. The magnetic shielding afforded by the earth's field cannot be relied upon for protection because during large solar proton events the earth's field is sufficiently disturbed to receive these normally excluded energies. Reference III-5 gives a detailed discussion of radiation doses from this type of radiation.

CENTER-OF-MASS LOCATIONS, PRINCIPAL AXIS LOCATIONS, AND PRINCIPAL MOMENTS OF INERTIA

The basic antropometric data on which this section is based can be found in Tables V, VI, and VII of Reference III-7.

The weight of a 21-lb pressure suit was distributed over the body segments in proportion to their tabular weights. The moments of inertia of the segments were scaled up proportionately to the increase in weight.

Table 5 shows the apportionment of the suit weight.

Table 5. Apportionment of Suit Weight to Body Segments

Body Segment	Suit Weight (lb)
Head (helmet)	5.5
Torso	4.0
Upper arm	0.7 each
Lower arm	0.5 each
Glove	0.25 each
Upper leg	1.3 each
Lower leg	0.9 each
Boot	2.1 each

It was assumed that the center of mass of each segment did not change when the suit was added.

Five postural variations representing the extremes likely to be encountered in flight were defined.

Figures 5 through 9 show the postures and coordinates of the hinge points and body segment centers of mass. The mass of each segment (including the portion of the suit covering the segment) is shown with the mass center coordinates.

Unless otherwise specified, the coordinates used are defined as follows:

- The origin is located at the center of mass of the man standing with suit and no backpack, in position 1.
- X-axis is horizontal with positive end coming out of the front of the man.

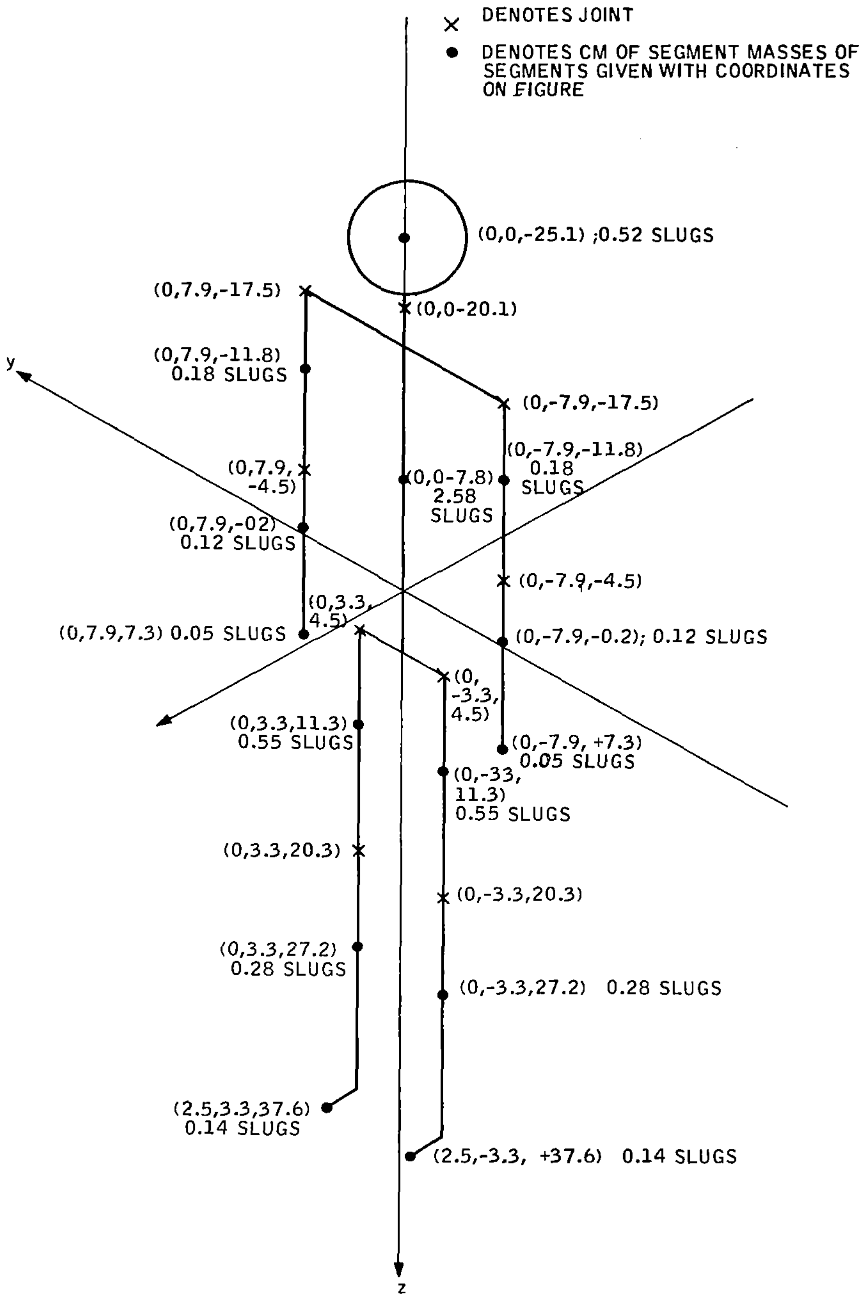

Figure 5. USAF Mean Man, Position 1

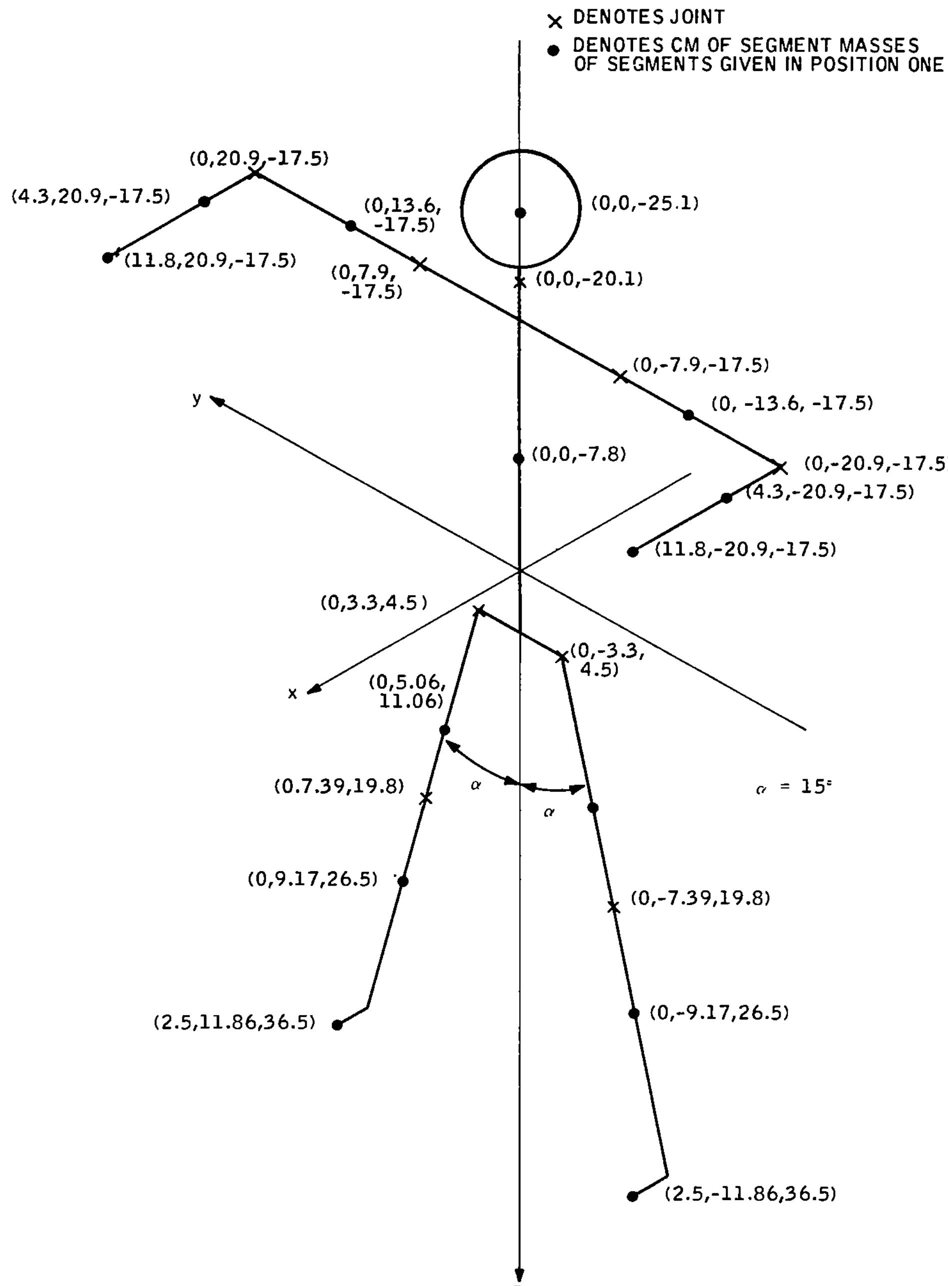

Figure 6. USAF Mean Man, Position 2

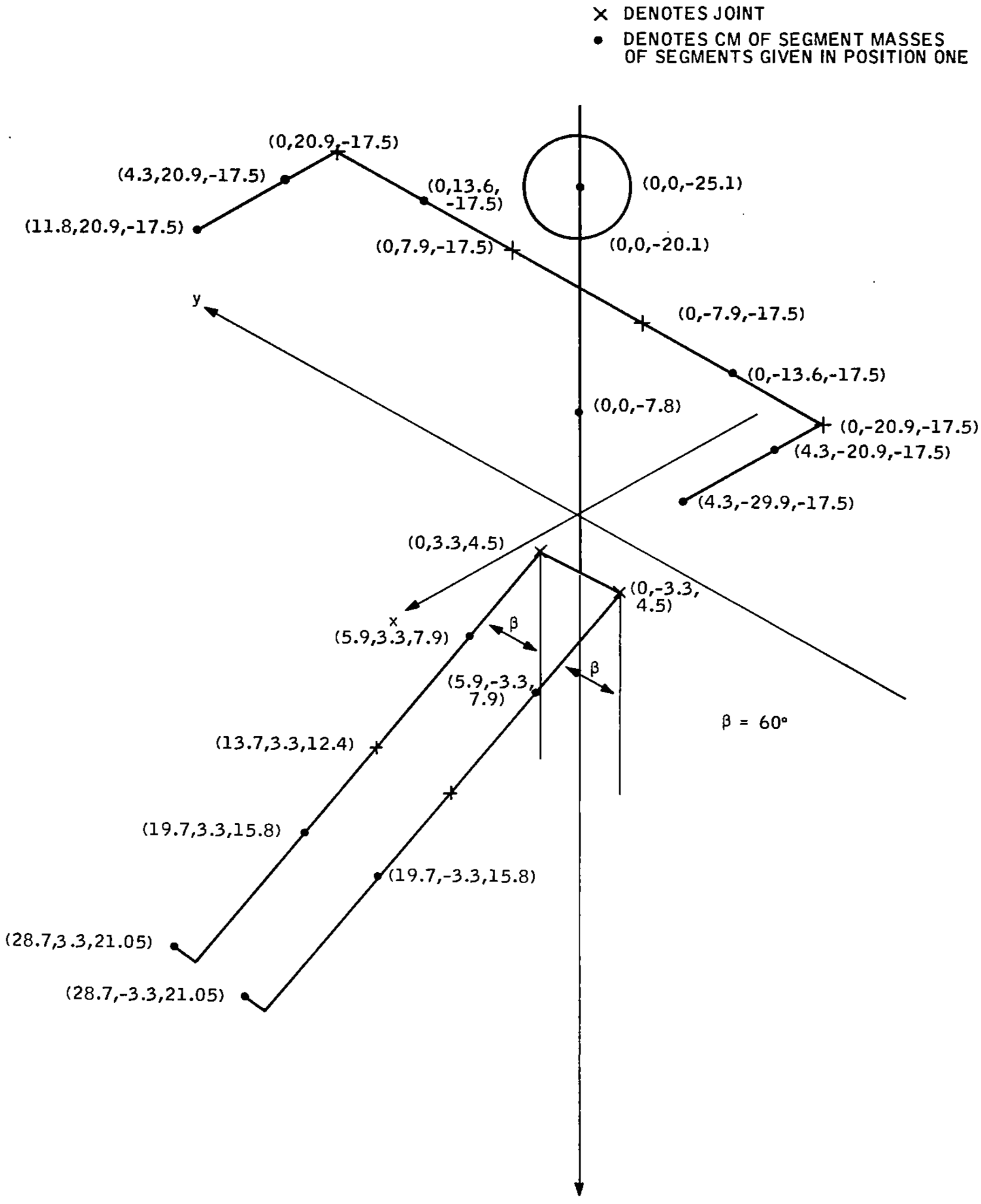

Figure 7. USAF Mean Man, Position 3

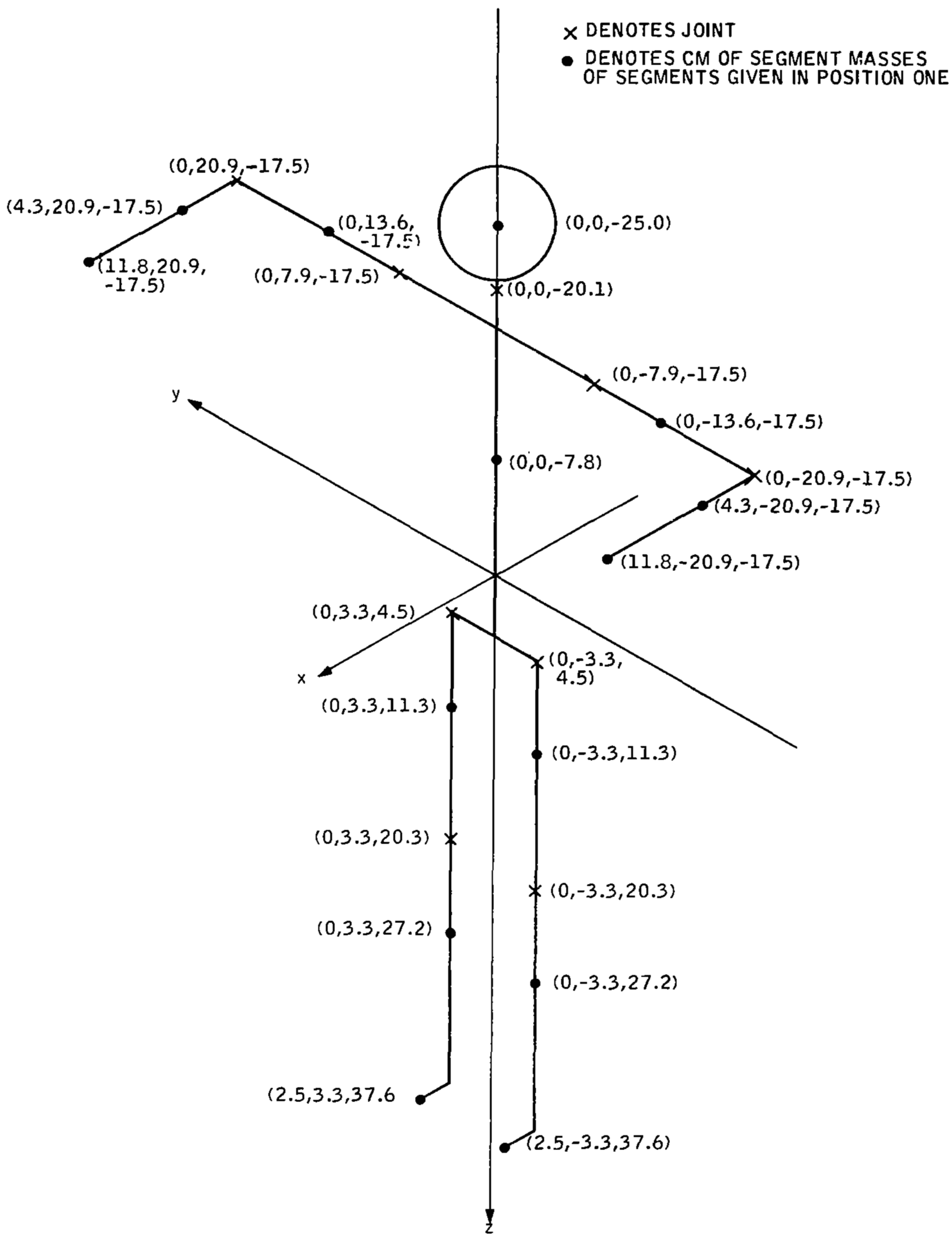

Figure 8. USAF Mean Man, Position 4

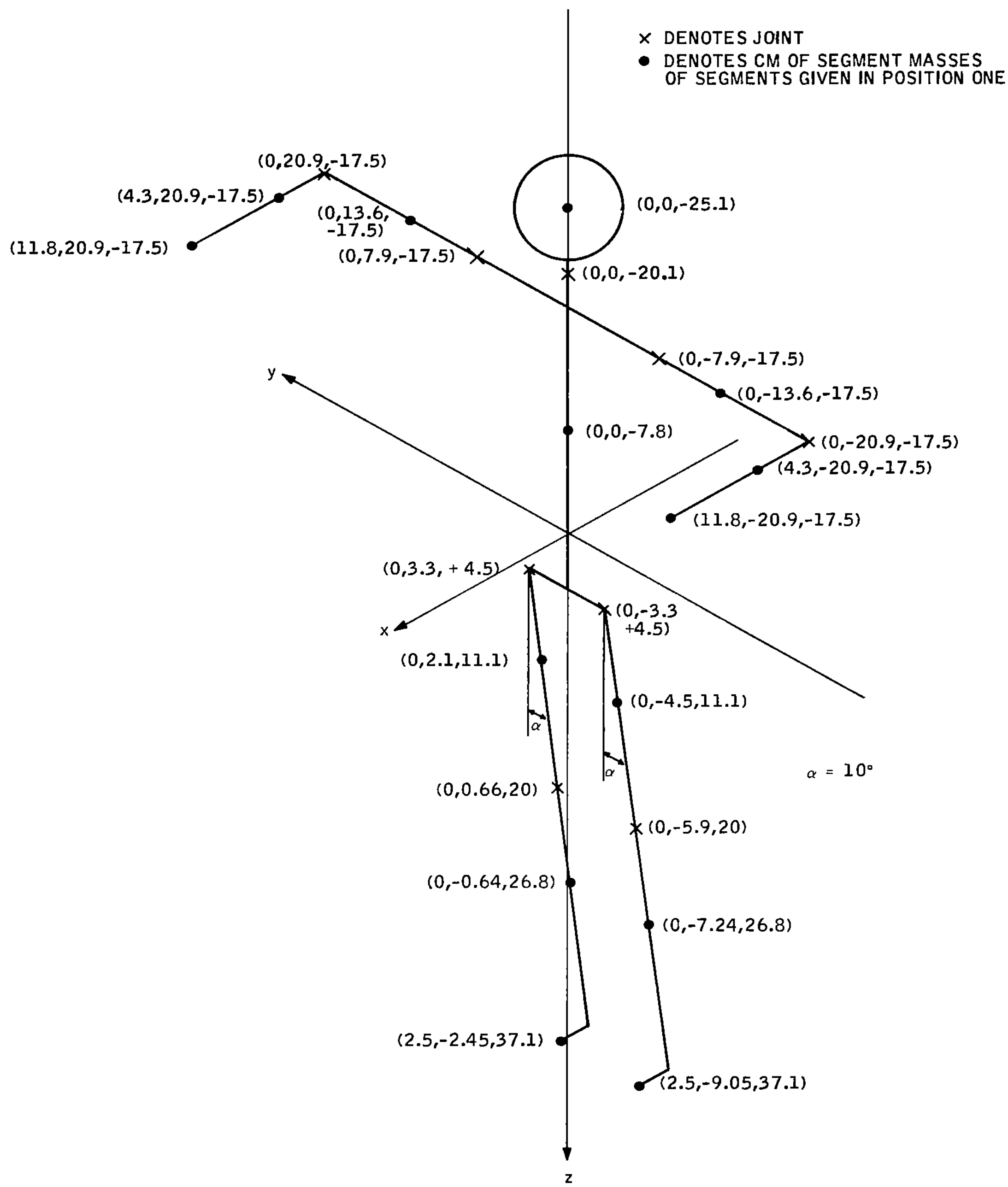

Figure 9. USAF Mean Man, Position 5

- Y-axis is horizontal with positive end coming out of the right side of the man.

- Z-axis is vertical with the positive end downward.

All of the coordinates given in Figures 5 through 9 are given in inches.

Center-of-Mass Locations

The backpack weight was assumed to vary between 120 and 190 lbs. Its dimensions were assumed to be:

Height: 41 inches
Width: 18 inches
Depth: 8 inches

Its center of mass is located at (-8. 5, 0, -7. 1). The backpack was assumed to be homogeneous.

The center-of-mass locations are given in Table 6.

Table 6. Location of Center of Mass of USAF Mean Man With Backpack and Pressure Suit

Position	120-lb Backpack	190-lb Backpack
1	(-3. 4, 0, -2. 8)	(-4. 3, 0, -3. 6)
2	(-3. 0, 0, -3. 7)	(-4. 0, 0, -4. 3)
3	(-0. 5, 0, -5. 1)	(-1. 9, 0, -5. 5)
4	(-3. 0, 0, -3. 6)	(-4. 0, 0, -4. 2)
5	(-3. 0, -0. 5, -3. 6)	(-4. 0, -0. 4, -4. 3)

Principal Axis Locations and Principal Moments of Inertia

The moments and products of inertia were calculated for use in simulations. Table 7 presents the results in matrix form. The typical matrix has the form:

$$\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix}$$

The moments and products of inertia are measured in slug-ft^2 about the center of mass of the particular configuration.

Table 8 shows the moments of inertia about the principal axes and the direction cosines from the coordinate systems of Table 7 to the principal axes.

Table 7. Summary of Moments and Products of Inertia

Position	120-lb Backpack	190-lb Backpack
1	CM(-3.35, 0, -2.795) $\begin{bmatrix} 14.984 & 0 & -1.180 \\ 0 & 15.084 & 0 \\ -1.180 & 0 & 2.735 \end{bmatrix}$	CM(-4.31, 0, -3.61) $\begin{bmatrix} 19.313 & 0 & -1.46 \\ 0 & 22.374 & 0 \\ -1.46 & 0 & 6.509 \end{bmatrix}$
2	CM(-3.035, 0, -3.66) $\begin{bmatrix} 19.214 & 0 & -0.745 \\ 0 & 17.410 & 0 \\ -0.745 & 0 & 4.662 \end{bmatrix}$	CM(-4.05, 0, -4.30) $\begin{bmatrix} 22.936 & 0 & -0.97 \\ 0 & 24.379 & 0 \\ -0.97 & 0 & 11.230 \end{bmatrix}$
3	CM(-0.538, 0, -5.12) $\begin{bmatrix} 13.121 & 0 & -3.81 \\ 0 & 16.142 & 0 \\ -3.81 & 0 & 8.338 \end{bmatrix}$	CM(-1.94, 0, -5.48) $\begin{bmatrix} 17.273 & 0 & -4.14 \\ 0 & 23.726 & 0 \\ -4.14 & 0 & 12.580 \end{bmatrix}$
4	CM(-3.035, 0, -3.57) $\begin{bmatrix} 18.020 & 0 & -0.766 \\ 0 & 16.961 & 0 \\ -0.766 & 0 & 4.066 \end{bmatrix}$	CM(-4.05, 0, -4.22) $\begin{bmatrix} 22.278 & 0 & -0.99 \\ 0 & 24.468 & 0 \\ -0.99 & 0 & 8.128 \end{bmatrix}$
5	CM(-.3.035, -0.545, -3.61) $\begin{bmatrix} 15.338 & 0.136 & 0.75 \\ 0.136 & 16.942 & 1.06 \\ -0.75 & 1.06 & 4.811 \end{bmatrix}$	CM(-4.05, -0.442, -4.26) $\begin{bmatrix} 19.742 & 0.012 & -0.982 \\ 0.012 & 24.444 & 0.98 \\ -0.982 & 0.98 & 9.023 \end{bmatrix}$

Table 8. Summary of Principal Moments of Inertia and Direction Cosines of Principal Axes

Position	120-lb Backpack	190-lb Backpack
1	Direction Cosines $\begin{bmatrix} 15.096 & 0 & 0 \\ 0 & 15.084 & 0 \\ 0 & 0 & 2.624 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.99553 \quad m = 0 \quad n = -0.09449 \\ \rightarrow \ell = 0 \quad m = 1 \quad n = 0 \\ \rightarrow \ell = 0.09532 \quad m = 0 \quad n = 0.99544 \end{array}$	Direction Cosines $\begin{bmatrix} 19.477 & 0 & 0 \\ 0 & 22.374 & 0 \\ 0 & 0 & 6.345 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.99244 \quad m = 0 \quad n = -0.11148 \\ \rightarrow \ell = 0 \quad m = 1 \quad n = 0 \\ \rightarrow \ell = 0.11170 \quad m = 0 \quad n = 0.99374 \end{array}$
2	Direction Cosines $\begin{bmatrix} 19.252 & 0 & 0 \\ 0 & 17.416 & 0 \\ 0 & 0 & 4.624 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.99869 \quad m = 0 \quad n = -0.05094 \\ \rightarrow \ell = 0 \quad m = 1 \quad n = 0 \\ \rightarrow \ell = 0.05099 \quad m = 0 \quad n = 0.99870 \end{array}$	Direction Cosines $\begin{bmatrix} 23.017 & 0 & 0 \\ 0 & 24.379 & 0 \\ 0 & 0 & 11.149 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.99654 \quad m = 0 \quad n = -0.08322 \\ \rightarrow \ell = 0 \quad m = 1 \quad n = 0 \\ \rightarrow \ell = 0.08202 \quad m = 0 \quad n = 0.99663 \end{array}$
3	Direction Cosines $\begin{bmatrix} 15.226 & 0 & 0 \\ 0 & 16.142 & 0 \\ 0 & 0 & 6.232 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.87528 \quad m = 0 \quad n = -0.48361 \\ \rightarrow \ell = 0 \quad m = 1 \quad n = 0 \\ \rightarrow \ell = 0.48397 \quad m = 0 \quad n = 0.87508 \end{array}$	Direction Cosines $\begin{bmatrix} 19.683 & 0 & 0 \\ 0 & 23.726 & 0 \\ 0 & 0 & 10.169 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.86423 \quad m = 0 \quad n = -0.50309 \\ \rightarrow \ell = 0 \quad m = 1 \quad n = 0 \\ \rightarrow \ell = 0.50351 \quad m = 0 \quad n = 0.86399 \end{array}$
4	Direction Cosines $\begin{bmatrix} 18.063 & 0 & 0 \\ 0 & 16.961 & 0 \\ 0 & 0 & 4.023 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.99842 \quad m = 0 \quad n = -0.05605 \\ \rightarrow \ell = 0 \quad m = 1 \quad n = 0 \\ \rightarrow \ell = 0.05464 \quad m = 0 \quad n = 0.99850 \end{array}$	Direction Cosines $\begin{bmatrix} 22.347 & 0 & 0 \\ 0 & 24.468 & 0 \\ 0 & 0 & 8.059 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.99757 \quad m = 0 \quad n = -0.06953 \\ \rightarrow \ell = 0 \quad m = 1 \quad n = 0 \\ \rightarrow \ell = 0.06946 \quad m = 0 \quad n = 0.99758 \end{array}$
5	Direction Cosines $\begin{bmatrix} 15.389 & 0 & 0 \\ 0 & 17.037 & 0 \\ 0 & 0 & 4.665 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.996561 \quad m = -0.03650 \quad n = -0.074385 \\ \rightarrow \ell = 0.042725 \quad m = 0.99558 \quad n = 0.083745 \\ \rightarrow \ell = 0.070932 \quad m = -0.086583 \quad n = 0.993709 \end{array}$	Direction Cosines $\begin{bmatrix} 19.829 & 0 & 0 \\ 0 & 24.507 & 0 \\ 0 & 0 & 8.873 \end{bmatrix} \begin{array}{l} \rightarrow \ell = 0.99599 \quad m = 0.016096 \quad n = -0.08804 \\ \rightarrow \ell = 0.011153 \quad m = -0.997698 \quad n = -0.066332 \\ \rightarrow \ell = 0.089882 \quad m = -0.062632 \quad n = 0.993977 \end{array}$

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SECTION IV
CONTROLLER INVESTIGATION

TYPES OF CONTROLLERS

A comprehensive human factors study was undertaken to investigate suitable controller configurations by which an astronaut, operating in extra-vehicular space, can provide desired command inputs to the ACS. Because of the unique goal established for the study -- that of minimizing the need for the astronaut to use his hands for controller operation -- conventional approaches to controller design were inadequate. Therefore, many different controller configurations were evaluated that would provide the functional performance and operational simplicity demanded by the program objectives.

The method followed during the study involved three steps:

- Definition of human factors requirements applicable to the AMU-ACS controller.

- Elaboration of all controller concepts considered feasible, along with their major characteristics.

- Analysis of each concept, including its possible method of mechanization, mode of operation, and suitability for the AMU.

Human Factors Requirements

The human factors requirements applicable to an ACS controller are:

- Use of the hands for controller operation should be minimized.

- Body and limb mobility, partially restricted by the pressure suit, should be preserved.

- Visibility must not be obstructed.

- Normal radio voice communication must not be interfered with.

- Integrity of the body, or any of its functions, should not be impaired.

While these requirements may be self-evident, the first deserves additional discussion. There are a number of reasons for assuming that one or both of the astronaut's hands should be continuously free and unhampered:

- The astronaut may be required to hand-carry tools or supplies for assembly, inspection, or repair purposes when outside his vehicle, or when traveling to another vehicle.

- He may need to use his hands to absorb part of the shock when landing on a target.

- He may need the use of his hands for holding or operating tools at the work site.

- He may need to grasp objects for towing.

- He may need to use his hands for grasping a hand hold or other restraint while working.

- He may need the use of his hands for holding or pulling on a tether line.

In view of the probability that at least one, and possibly more, of these requirements may be appropriate at all times, serious consideration was given to design of a controller that could be actuated by means other than the hands.

Summary of Controller Concepts

The basic literature on the design of controls (References IV-1, IV-2, IV-3, IV-4, IV-5 and IV-6) deals almost exclusively with conventional devices, such as push buttons, switches, cranks, and foot pedals. Since use of these types of controls is precluded by the conditions and constraints under which the astronaut is operating, an extensive investigation of unconventional controls was performed. A tabulation of all the controls considered feasible, along with their major characteristics, is presented in Table 9. The following characteristics have been tabulated:

- Mechanization -- a description of the mechanism used to sense the human control outputs.
- Output characteristics -- whether the controller provides an output that is continuously variable or on-off; and, if the latter, whether the output is incremental.
- Location -- the most likely location for the controller on the body of the astronaut.
- Command capability -- whether the controller can provide complete authority over three degrees of freedom in rotation, three degrees of freedom in translation, and switching.
- Hand freedom -- whether one hand is required for controlling or for switching.

Table 9. Controller Concepts

CONCEPT		CHARACTERISTIC																	
Controller	Type	Mechanization	Output	Location	Command Capability	Provides Hand Freedom	Accessibility	Natural Direction of Operation	Accuracy	Cross Coupling Between Rotational Axes	Motion Coupling	Acquisition Actuation	Inadvertent Actuation	Type of Feedback	Response Time (sec)	Present Design Status	Reliability	Size*	Weight*
Hand	On chest or side	Electro-mechanical pencil stick	Continuously variable or on-off	On chest, stomach or hip	Complete	One hand free	Good for both hands	Yes	±1° or less	Not significant with small stick excursions	Not significant at small accelerations	Probable	Not probable except in cramped quarters	Visual, force	1.0-1.5 (0.5-1.0 reach plus 0.5 operate)	Can be designed now	Good. Can be simple, rugged,	1	1
	In auxiliary glove	Possibly push buttons	Continuously variable or on-off	Back of glove	Complete	One hand free	With one controller for each hand, accessibility good for either hand	No	±1° if continuously variable, on-off N/A	Not significant	Not significant	None if properly designed	Not probable	Visual, possibly force	1.5-2.5 (1.0-2.0 reach plus 0.5 operate)	Requires moderate development	Good. Simple, rugged, repeatable	1	1
Oral	Voice	"Audrey", "Sceptron", "Shoe Box", etc.	On-off or incremental	At throat	Complete	Both hands free	Good	No	N/A	Not possible	None	None	Not probable if unique sounds reserved for commands	Visual	0.5	Requires extensive development	Good. Simple, repeatable	5	4
	Tone	Resonant transducers	On-off or incremental	At throat	Complete	Both hands free	Good depending on musical ability of operator	No	N/A	Not possible	None	None	Not probable	Visual	0.5	Requires extensive development	Good. Simple, repeatable	3	2
	Breath	Sensitive diaphragms in "mouth organ" configuration	On-off or incremental	In front of mouth	Complete	Both hands free	Good	No	N/A	Not possible	None	None	Not probable if sensor thresholds are high enough	Visual	0.5	Requires extensive development	Good. Simple, repeatable	3	2
	Tongue	Very low-pressure switches	Probably on-off	On lips or in mouth	Unknown	Both hands free	Good	Perhaps Yes	N/A	Not possible	None	None if properly designed	Not probable if properly designed	Visual	0.5	Requires extensive development	Probably good	3	2
Eye	Reflected beam	Light beam reflected from cornea	Continuously variable	At eye	Forward translation only	One hand may be required for supplemental control and switching	Good	Yes	±10 min at center of field, ±1° at edge of field	Not possible	None	None	Not probable if lockout switch included	Visual	0.1	Requires extensive development	Fair. Excessive equipment, tendency to misalignment	5	3
	Corneal-retinal potentials	Electrical potential across eye	Continuously variable	At eye	Forward translation only	One hand may be required for supplemental control and switching	Good	Yes	±1-2°	Not possible	None	None	Not probable	Visual	0.1	Requires extensive development	Fair. Extraneous signals spurious variations, frequent miscalculations	5	3
	Muscle action potentials	Electrical signals in eye muscles	Continuously variable	At eye	Forward translation only.	One hand may be required for supplemental control and switching	Good	Yes	Unknown	Not possible	None	None	Not probable	Visual	0.1	Requires extensive development	Fair. Variable contact resistance, excessive electronics	5	3
Body	Head	Electrical or mechanical pickoffs sensing position of heads relative to body	Continuously variable	Sight at eye, pickoffs at neck	Forward translation only or rotation only	One hand may be required for control or switching	Good	Yes	With sight ±3 mils, without sight ±1°	Not possible	Not significant	None	Possible unless lockout is used	Visual	0.5 Movement plus fixation time	Requires extensive development	Probably good	1.5	1.5
	Limb motion	Force or displacement sensors attached to limb	Continuously variable or on-off	At controlling limb	Can be complete	One hand may be required for control or switching	Good	Perhaps Yes	±1-2°	Possibly some	Possible, not probable at low thrust levels	None	Possible	Visual	0.3-0.5	Requires extensive development	Probably good	1.5	1.5
	Myoelectronics	Skin electrodes sensing muscle action potentials	On-off or incremental	At controlling limb	Can be complete	Both hands free	Good	Perhaps Yes	N/A	Not significant	Possible	None	Possible	Visual	0.2	Requires extensive development	Fair. Variable contact resistance, excessive electronics	5	3

*Normalized with respect to hand controllers

- Accessibility -- for hand controller, whether it is easily accessible to one or both hands; for non-hand controllers, whether it is easily accessible to the actuating body member.

- Natural direction of operation -- whether the resulting maneuver is isomorphic with the astronaut's control input.

- Accuracy -- the precision with which commands can be made.

- Cross coupling -- whether excursions of the controller in one axis of rotation can be confusing to the astronaut, causing him to cross-control when applying inputs to the other axes.

- Motion coupling -- whether actuation causes a maneuver that sets up inertial forces tending to cause inadvertent actuation.

- Acquisition actuations -- whether acquiring of the control may be accompanied by jostling or fumbling.

- Inadvertent actuation -- whether the controller is subject to accidental operation when not in use.

- Type of feedback -- the kind of feedback to the astronaut by which he can gauge the adequacy of his inputs.

- Response time -- the time required to reach, acquire, and operate (generate an electrical command signal to the ACS) the controller.

- Present design status -- an estimate of the amount of development required to design the controller.

- Reliability -- an estimate of controller simplicity, ruggedness, and repeatability.

- Size -- an estimate of controller size with respect to hand controllers.

- Weight -- an estimate of controller weight with respect to hand controllers.

Analysis of Controller Concepts

The controller concepts presented in Table 9 are discussed and evaluated in this section.

Hand Controllers -- Although use of a hand controller as a primary control device is obviated by the requirement for hand freedom, a discussion of hand controllers is included because they may merit consideration as auxiliary, backup or emergency controllers under some circumstances.

Three types of hand controllers were considered. A "squeeze" type which requires a flexing action of the palm was immediately eliminated from consideration when it was found that all pressure suit gloves examined have a built-in metal strap across the palm to prevent the glove from ballooning upon inflation. Since the strap also prevents closing of the palm, no further consideration was given to this type of control.

If a requirement for continuous freedom of the hands did not exist, a conventional pencil stick would probably provide the most efficient controller with the least time required for development and design. Sidesticks and pencil sticks have been evaluated for both aircraft and space vehicles, and have been found satisfactory for most situations. Various pencil stick configurations providing rotational and translational control inputs to the AMU were extensively considered by Griffin (Reference IV-7). Primary considerations governing the design of a pencil stick controller for the AMU application are:

- Accessibility -- The arm of the inflated suit has markedly reduced mobility. The controller must be readily accessible, so it must be located within easy reach of the arm. Areas most easily accessible on the inflated suits currently considered for space travel are the chest, stomach, and hip. The former two are probably superior because the frontal area is accessible to both hands.

- Functional simplicity -- A hand controller consisting of several rotating knobs, thumbwheels, slide switches, or some combination of these, would be quite difficult to use because of the drastically reduced dexterity of the fingers in the glove of an inflated pressure suit. A pencil stick configuration would seem to be the simplest type of hand controller from several standpoints: The control of several axes can be coordinated in one maneuver, its direction of operation is isomorphic with the resulting motion, and visual reference to the controller is not required.

- Dynamics -- The operating characteristics of a pencil stick are easily adjusted, during the design stages, to the point of maximum compatibility with the human. Force levels, friction, excursions, size, etc., can all be selected to minimize inadvertent actuation and cross-coupling, and to maximize accuracy and feel characteristics.

The detailed configuration of a pencil stick controller suitable for the AMU application has not yet been determined. There appear to be two basic alternatives. The first -- designing one stick capable of six degrees of freedom -- would satisfy all rotational and translational command requirements. The possibility of cross-coupling and inadvertent actuation would seem to be heightened with such a controller, to say nothing of the difficulty of mechanization. The second alternative is to provide two sticks, at right angles to and separated from each other, one of which controls rotation and the other translation.

The auxiliary glove concept uses the excellent qualities of the fingers for control purposes and yet permits use of the same hand for grasping and holding. A pocket, or large cavity, could be built up on the back of the existing glove. The hand could then be inserted into this pocket and a suitable control mechanism operated with the fingers. Since both gloves could be thus equipped, redundancy is automatically achieved with this concept. Preliminary investigations of subjects in inflated pressure suits have shown that the primary condition exists for feasibility of this concept: The arm can easily be withdrawn up the sleeve the inch or two required to permit the hand to slip into the auxiliary glove.

The advantages of this concept are:

- The controller accessibility is good for either hand.
- Redundancy is provided.
- The restraint of the suit to arm mobility is not a factor.
- There is no interference with the normal grasping functions of the primary glove.

The exact details of the controller configuration inside the auxiliary glove have not yet been worked out. The controller may be a small set of push buttons, a "rolling ball", a pencil stick, or some other configuration.

Since hand controllers have been eliminated from consideration as a primary controller for reasons mentioned previously, they will not be discussed further.

Eye Controllers -- An AMU attitude control system that utilizes outputs taken directly from the astronaut's eye is attractive for several reasons:

1. The eye is an optical error-detecting device that is self-correcting. Thus, a control system that is slaved to the eye would automatically receive the correct inputs appropriate to its assigned function of translating to a point, simply by virtue of the operator steadily observing a target.

2. The accuracy of the eye -- on the order of 3 mils or less -- appears to make it a more precise controller than other forms of manual control.

3. Reliance on the eye for control outputs would free the hands for the grasping and holding actions required during maintenance and rendezvous.

There are three major methods of measuring eye motion:

- Sensing the deflection of a beam of light reflected off some portion of the eye.
- Sensing the vector position of the front-to-back potential of the eye.
- Sensing the action potentials of the eye muscles.

The beam-of-light technique requires that a light source generate a beam of light that is reflected off some portion of the eye. Movement of the eye causes a movement of the beam which is sensed by a device that develops an electrical signal proportional to the movement of the eye. Light beams have been reflected from the cornea (References IV-8 and IV-9), from the optic disc (References IV-10), and from a mirror mounted on a contact lens (Reference IV-11). The sensing devices used include multiple photo cells (Reference IV-11) and a TV camera (References IV-8 and IV-9).

Specific problems in the application of the reflected-beam technique to the AMU include the following:

- The equipment currently required is excessive. The light-generating equipment, the beam sensing equipment (e.g., photo cells, TV camera), and the associated electronics prohibit its practical consideration in the AMU application at the present level of development.

- Like all accurate optical measuring equipment, precise initial alignment is required. Whether this alignment can be maintained under the continual donning and doffing of the helmet needs investigation.

Determination of eye position by measurement of the position of its corneal-retinal (front-to-back) potential utilizes the fact that the eye behaves like a small battery. It is electrically positive at the front (cornea) and negative at the back (fundus). Whenever the eye is moved in its socket, pairs of electrodes placed above and below the eye, and on each side of the eye, will sense the rotation of front-to-back potential in terms of vertical and horizontal components.

Specific objections to the measurement of corneal-retinal potential include the following (Reference IV-12):

- Extraneous signals relating to muscle action potentials and galvanic skin response may be inadvertently sensed.

- The corneal-retinal potential will give spurious variations with the diurnal cycle, changes in dark adaptation, etc.

- Equipment would have to be tailored to an individual user, and probably calibrated frequently (perhaps as often as every 2 to 3 hours).

- The electrodes suffer from variability in contact resistance resulting from transient changes in galvanic skin response.

The technique of measuring eye muscle signals has been attempted only imperfectly. Eye muscle activity has been recorded by electrodes placed subcutaneously, the recordings consisting of both frequency of firing single motor units and number of units activated. It is suggested (Reference IV-12, p. 12) that eye position information might be derived from records of this type by integrating the signals from a group of muscles and comparing the integrated output with calibration data.

Objections to the measurement of muscle action potentials are generally the same as those given for corneal-retinal potential measurement. Subcutaneous electrodes are used to avoid the unreliability of external electrodes, but the discomfort associated with their use eliminates this method from further consideration.

From functional considerations, it is also clear that eye controllers are not controllers in the strictest sense, but merely aiming devices that could provide steering information to the AMU. The ACS still needs command inputs to remove or insert the eye in the control loop, to provide an "execute" signal at the proper time, and to command a fast or slow speed of execution.

The review of concepts considered for eye controller applications has shown that none are adequate to meet the requirements of the AMU situation.

Head Controllers -- The head may be used as a controller in two ways: with and without a visual sighting mechanism. When used in conjunction with a sight, the controller concept is similar to the eye controllers discussed subsequently, in that the astronaut establishes a light-of-sight between himself and the target. Pickoffs, sensing the relative position of the helmet to the AMU, then provide signals to the ACS translating the astronaut to the observed target. Many of the comments applicable to the eye controller are applicable here: within the scope of the operator's field of view, the helmet controller is a simple and accurate aiming device. However, auxiliary controls will still be required for activation, speed selection, execution, rotation, and backward translation.

Another way of using the head as a controller is to instrument the helmet so that signals are generated by the nods, turns, and tilts of the head. These three motions could well command corresponding motions of the astronaut: nodding commanding pitch, turning commanding yaw, and tilting commanding roll. It is difficult to conceive how head motions could provide translation commands to the ACS. Speed level selection and execution commands would undoubtedly have to be supplied by auxiliary controls.

Perhaps the strongest argument against the use of the head as a controller is that it may interfere with the visual function. The importance of a lockout or disengage switch is highlighted when the head movements associated with considerable visual scanning must be interspersed with the head movements associated with attitude control.

Torso Controllers -- Control inputs produced by twisting and bending the torso might seem, at first glance, to be a convenient and natural method of achieving attitude control. This method of control is probably not feasible, however, for several reasons. First, the back-pack is securely strapped to the astronaut so that there is virtually no movement between the two. Second, even if relative movement could be allowed for control purposes, the resulting thrust might very well cause inadvertent operation of the ACS. In any case, the close mechanical intercoupling between the AMU and the torso seems to preclude the kind of fine control needed for efficient, accurate attitude control. Lastly, even if rotational commands were allocated to the torso, speed, execution, and translational controls would still have to be provided elsewhere.

Leg and Foot Controllers -- Use of the feet and legs for control is fairly common: automobiles and aircraft immediately come to mind. One of the differences between, for example, an auto accelerator or aircraft rudder pedal, on the one hand, and the AMU-ACS application on the other is that in the former the foot and leg are operating in only one degree of freedom. For the ACS, the leg or foot would be taxed with controlling in six degrees of freedom, and it is not immediately apparent how this would be accomplished.

Several additional objections could be raised against the leg or foot controller concept: For a standing, free-floating operator, the feet and legs will not provide sensitive modulated control. Incremental on-off control could be provided, but again the question of which movements control which axes is uncertain. One of the primary disadvantages of leg control is the high inertial forces that would be generated by the mass of the legs acted on by the thrust, and the resulting motion coupling between the leg and the actuating controls. Use of the legs or feet may also entail a loss of worker mobility at the work site, particularly if the mechani-zation is external to the pressure suit. Loss of maneuverability and mobility at the work site was the primary reason for excluding foot and leg controls from consideration in one experimental AMU program (Reference IV-7).

Myoelectronics -- Since Galvani's experiments on the muscles of a frog's leg in the late 1700's, it has been demonstrated that most processes in living organisms are accompanied by electrical changes. It has been known for some time that the actions of the voluntary muscles in operating the limbs of the body are accompanied by small electrical signals. Utilization of these signals for control purposes has become increasingly intriguing. In the study of bio-electrical phenomena, substantial results have been achieved in the area of the brain (electroencephalography), the heart (electrocardiography), and the eye (electroretinography). Considerable attention is now being devoted to the study of amplitude and frequency characteristics of biocurrents of the skeletal muscles (electromyography) for the purpose of utilizing the currents for actuation of external devices. The kind of application now receiving most attention is the operation of prosthetic devices by amputees.

Raw electromyographic signals are characteristically spiked, with amplitudes in the high micro- and low millivolt range. A practical, reliable technique must be developed for the sensing, amplification, filtering, conditioning, and decoding of these signals for command and control purposes. The problem of using bio-electric signals to control the AMU can be divided into several simpler problems. First, a simple, effective method for sensing electric signals in the astronaut must be perfected. The sensors must be easy to apply and remove, and com-fortable to wear since they may be worn for long periods of time. Second, suitab amplifiers, signal conditioners, and decoders must be developed which can discriminate between wanted and unwanted signals, and can use the wanted sig-nals for control purposes.

Bioelectric signals would undoubtedly be useful for command and control where the human operator finds normal manual control difficult or impossible by reason of restraint, distance, danger, etc. Until the technical problems are solved, however, the concept of electromyographic control does not seem to have any practical applicability to the attitude control system of the AMU.

Oral Controllers -- The region of the mouth offers some attractive control potentialities, when the number and variety of elements available are considered: the lips, the tongue, the teeth, the breath, speech, singing, whistling, etc. Several types of oral controls were considered briefly and rejected as bizarre and impractical, among them control by the lips and tongue. The feasibility of devices which attach to or are operated by the lips or tongue is questionable, first from the standpoint of space available within the helmet, but most important from the standpoint of their acceptability to the astronaut.

Meriting closer examination are the following concepts which use the voice and breath:

- Breath control
- Tone control
- Speech control (voice controller)

Breath Controllers -- Among the concepts considered for an ACS controller was that of a breath-operated device. The model for a breath-operated mechanism is, of course, the harmonica, or mouth organ, known chiefly as a child's toy and an amusing instrument for casual musical entertainment. The principle of a breath controller deserves serious consideration, even if only momentarily, because it too, like voice and tone controllers, offers the maximum amount of operational simplicity to the astronaut, in the sense that no mechanical, electrical, or optical devices require manipulation by hands, head, or other body members. In addition, the breath controller may be relatively simple to mechanize since the sensors can be similar to those used in the harmonica itself: small pressure transducers which resonate at their natural frequency when mechanically excited. Outputs from the controller could be incremental or continuously variable.

For this analysis, it was assumed that the astronaut will need 10 commands to exercise complete manual control over the ACS. There are then two alternative ways of implementing a breath controller. First, the astronaut can be provided with an oblong frame located a short distance in front of his mouth in which are 10 pressure-sensitive pickups. A desired signal is generated simply by the operator blowing in the proper direction. Enough distance should be introduced between the sensors, and dividers used as well, to obviate the possibility of the wrong sensor being activated.

In spite of certain advantages of this type of breath controller, such as its provision for complete hand freedom and its relative ease of mechanization, it suffers from a number of serious disadvantages:

- Additional oxygen requirements, though small, are a matter of concern in an environmental system such as the AMU, where the capacity is very limited.
- Because of its location in front of the mouth, the breath controller may interfere with communication equipment.
- The added breathing requirements may increase the amount of moisture in the suit atmosphere significantly. In a delicately balanced system, this increase cannot be ignored.
- There is no arrangement of pickups that can give the controller input-response compatibility. All input locations are somewhat arbitrary and would have to be learned. This factor may not be important, except that under conditions of great stress regression occurs, during which highly artificial relationships are temporarily forgotten.
- Directional control of the breath is not very precise, by normal engineering standards. The accuracy requirements may be incompatible with the dimensions of the airstream, the size of the sensors, and the control of the lips. If an incompatibility exists -- and only a feasibility study can determine whether this is so -- the possibility of inadvertent actuations is, of course, substantially increased.

A second method is to provide the astronaut with tiny mouthpieces which his lips can actually contact. The mouthpieces would conduct his breath to the proper area, precluding the possibility of activating the wrong sensor. But even more important, the use of mouthpieces permits control to be exercised by inhalation as well as exhalation, thus reducing the number of mouthpieces to five. Although the mouthpiece breath controller has certain attractive features, such as providing for hand freedom and ease of mechanization, its disadvantages are serious and appear to outweight the advantages:

- The mouthpiece controller will impose small additional oxygen consumption requirements on the environmental control system.
- Interference with communication equipment in the oral area inside the helmet is a distinct possibility.
- With the exception of x-axis translation commands, the controller lacks inherent stimulus-response compatibility, i.e., the inputs have no natural kinematic relationships to the resulting maneuvers.

In summary, it can be said that breath controllers possess some attractive features: they provide complete hand freedom; are relatively simple to mechanize; and lend themselves to on-off, incremental, or (in the case of the mouthpiece type) proportional commands. However, the disadvantages of an increased burden on the environmental control system, the space limitations inside the helmet, and the artificiality of the control code seem to be decisive.

Tone Controllers -- The tone controller concept deserves consideration because it accords the astronaut complete freedom for his hands and holds promise of being relatively simple to mechanize. In addition, the tone controller lends itself to remote control, an operational feature of no small importance. However, the following disadvantages far outweigh the advantages and make the tone controller concept unfeasible:

- The use of a singing or humming tone for control purposes would be completely unfamiliar to all astronauts. Considerable training would be required before a tone controller could be used with confidence. In the event of an emergency, it is quite possible that sudden emotional stress could temporarily cause a complete breakdown of the musical control ability.

- A tone controller imposes added oxygen supply and moisture removal requirements on the environmental control system. The added loads result from the greater breath consumption required for singing than for speaking. These added requirements, though small, may be significant.

- A tone controller necessitates providing a side tone (a reference for proper tone selection) in the earphones of the astronaut. This constitutes an additional complexity in the communication circuitry, a minor interference with the communication link, and a nuisance to the astronaut.

- It is doubtful that a tone controller could be used by astronauts of average musical ability with the accuracy and rapidity required for adequate AMU control. This is especially true at the initiation of a singing command (the "attack"): the fidelity to pitch of the very beginning of a singing tone is surprisingly poor, even among accomplished singers (Reference IV-14). In addition, the common technique of going from one note to another portamento style (a smooth gliding from one vocal tone to another through the intervening tones) would have to be scrupulously avoided.

- The tone controller must rely upon musical skills not naturally possessed to any marked extent by the average astronaut, not easily acquired, and not functionally dependable in an emergency.

Voice Controllers -- From the earliest stages of investigation into possible controller configurations, it became increasingly apparent that voice-operated mechanisms constituted an attractive method by which an astronaut could provide input commands to the ACS. The voice controller seemed to offer, above all else, operational simplicity for the astronaut: to perform a maneuver, all he had to do was speak. No mechanical encumbrances or equipment manipulations were required.

To establish the validity of the voice control concept, a feasibility study was undertaken that consisted initially of conducting a limited survey to ascertain what companies were involved in speech recognition work, and to determine the current state-of-the-art in this field. For discussion purposes, certain assumptions were made regarding the nature of verbal inputs to the ACS:

- Natural language words, numbers, or artificial words would be acceptable.
- Vocabulary size would be on the order of 10 words.
- An error by the operator or controller is tolerable as long as it is easily and quickly correctable.

When results of the preliminary survey were evaluated, it was concluded that suitable voice recognition devices were feasible. Although no devices are currently available that suit the ACS controller requirements exactly, a modest development program should result in a controller that would meet most operational and technical criteria. The attractive advantages of a voice controller are that the operator's hands and body are completely free from control motion responsibilities, and that complete control over attitude, translation, and speed changes can be achieved with a simple act of mind and tongue. In addition, a voice controller lends itself to remote control of the AMU in case the astronaut becomes incapacitated.

Selection of a Controller Concept

The voice controller was selected as the concept to be developed during this study because it offers the following advantages:

- It frees both hands for work tasks.
- It requires very little physical effort.

- It is not subject to inadvertent actuation.
- Lends itself readily to remote control.
- Performance requirements for the AMU are attainable.

Its principal disadvantage is the need for considerable development before flightworthy hardware is ready.

VOICE CONTROLLER REQUIREMENTS

This section deals with the human factors aspects of the following speech controller considerations:

- The size of the control vocabulary
- The choice of words for the command vocabulary
- The command code: the syntactical structure of the input
- Continuous command mechanization
- Multi-axis control
- Deadband control

Size of Control Vocabulary

The size of the control vocabulary is determined by two factors:

1. The number of commands the astronaut must have initially to exercise complete authority over his attitude control system.
2. The amount of "doubling up" that can take place in the interest of reduced controller size and weight. By "doubling up" is meant the use of a verbal command v in a repetitive manner to replace another verbal command w. This technique will be discussed more fully subsequently, but for the present analysis it is assumed that a limited amount of doubling up is permissible.

The astronaut will require verbal commands corresponding to control over the following parameters:

Control Variables	No. of Commands
Roll rate at 0.15, 3.0, and 20 deg/sec, positive and negative directions	6
Pitch rate at 0.15, 3.0, and 20 deg/sec, positive and negative directions	6
Yaw rate at 0.15, 3.0, and 20 deg/sec, positive and negative directions	6
X-axis acceleration at 0.3 and 3.8 ft/sec^2, positive and negative directions	4
Y-axis acceleration at 0.2 and 3.0 ft/sec^2, positive and negative directions	4
Z-axis acceleration at 0.2 and 3.0 ft/sec^2, positive and negative directions	4
Execute	1
Clear (remove previous commands)	1
Wide Deadband	1
Narrow Deadband	1
Stop	1
Cage (ACS synchronous mode)	1
Total	36

Thus, it appears that the astronaut will require a maximum of 36 commands to exercise complete attitude and translational control through his ACS. It is clear that the use of 36 separate and unique commands would impose an unnecessarily complicated burden on the astronaut. Considerable reduction can be effected by using the same maneuver command (e.g., "roll") for all maneuvers of that type, with direction and speed requiring additional command modifiers. Additional simplification can be achieved by the "doubling up" process: the use of one verbal command, in a repetitive manner, to constitute another command. (For example, the repetitive use of an axis command, "roll", as a speed command, high speed being "roll, roll, roll".)

The 36 verbal command requirements of the voice controller are classified in Table 10. All commands can be formed as a combination of the elements in columns 1 and 2. For example, a negative yaw rate, performed at intermediate speed, could be achieved by a command which consists of some combination of the words representing "yaw" and "minus". Possible words and combinations are explored in the following subsection. The point to be learned from Table 10 is that 36 commands can be formulated by using only 10 different words, i.e., the words representing:

1.	Roll	6.	Z
2.	Pitch	7.	Plus
3.	Yaw	8.	Minus
4.	X	9.	Stop
5.	Y	10.	Cage

Table 10. Classification of Verbal Command Requirements for Voice Controller

Column 1	Column 2	Precision Speed	Low Speed	High Speed
Roll	+	f (col 1, col 2)	f (col 1, col 2)	f (col 1, col 2)
	-	"	"	"
Pitch	+	"	"	"
	-	"	"	"
Yaw	+	"	"	"
	-	"	"	"
X	+		"	"
	-		"	"
Y	+		"	"
	-		"	"
Z	+		"	"
	-		"	"
Execute		Not a separate command, but a function of other commands		
Clear		Not a separate command, but a function of subsequent commande or of "stop" command		
Wide Deadband		Not a separate command, but a function of other commands: wide = stop - plus		
Narrow Deadband		Not a separate command, but a function of other commands: narrow = stop - minus		
Stop		f (col 1)	f (col 1)	f (col 1)
Cage		"	"	"

Choice of Words for Command Vocabulary

The designer has three choices when selecting a vocabulary for the speech controller:

A. The words can be selected from conventional language and can be related to the ACS responses in a direct, natural way; i.e., "roll" means roll, "pitch" means pitch, etc.

B. The words can be familiar words ("one", "two") related to the ACS responses in an unfamiliar, arbitrary manner; i.e., "one" means roll, "two" means pitch, etc.

C. The words can be unfamiliar, arbitrary sounds especially manufactured for this application and having desirable phonetic qualities that make them easy to utter and to recognize.

The advantages and disadvantages of each method of vocabulary construction are tabulated in Table 11. As can be seen from this table, many of the advantages and disadvantages hinge upon the accuracy and reliability of the voice recognition system of the controller. For example, one of the advantages given for the vocabulary consisting of artificial terms is that sounds having optimum acoustical properties can be selected, thus slightly increasing controller reliability. However, if it is assumed that completely adequate word recognition equipment will be available when the AMU becomes operational, the advantages and disadvantages based on this factor are eliminated and a choice between types of vocabularies can be made on other grounds.

If the availability of an accurate and reliable speech recognition device is assumed (and this appears to be a reasonable assumption in the light of the ground rules of the ACS study program), it is clear that vocabulary A (conventional terms used conventionally) has more advantages and fewer disadvantages than the other types.

Table 11. Types of Vocabularies for Voice Controller

Type of Vocabulary	Advantages	Disadvantages
Conventional terms used conventionally (Type A)	1. Commands are already familiar. 2. Virtually no verbal training required. 3. No memory loss.	1. Use of common terms slightly increases possibility of inadvertent actuation. 2.* Common terms may not be optimum for speech recognition device, reducing reliability slightly.
Conventional terms used arbitrarily (Type B)	1. Words are familiar, do not need to be learned. 2. Permits selection of terms not likely to occur in ordinary communication. 3.* Permits selection of phonetically desirable words.	1. Arbitrary relationship between words and ACS responses requires training. 2. Use of common terms permits slight possibility of inadvertent actuation.
Artificial terms (Type C)	1. Since terms do not occur in ordinary conversation, little likelihood of inadvertent actuation. 2.* Permits selection of sounds having optimum acoustic properties, slightly increasing controller reliability.	1. Large amount of training required to learn artificial sounds and artificial sounds and arbitrary meanings. 2. Possibility of temporary forgetting under great stress.

*Not valid if an accurate and reliable speech recognition device can be assumed.

In fact, vocabulary A has only one possible disadvantage: the command words might occur in normal communication between astronauts, inadvertently actuating the ACS. The probability of this happening is extremely small, however, considering that several command words must be uttered in the right sequential order. If the astronauts are specifically trained to avoid the use of command words in normal communication, the probability that command words will be inadvertently uttered, and that they will occur in the right sequence, is small indeed.

The foregoing considerations strongly imply that vocabulary A is to be preferred for the operational use of a speech controller. The terms, and their associated meanings, are extremely familiar to the astronaut using them; virtually no training would be required to learn articulation, timing, etc.; there is small likelihood of memory loss, even in an emergency; and the probability of inadvertent actuation is quite remote. In the light of these arguments, a vocabulary is set forth in Table 12 to meet operational and human factors requirements. The 10 words being proposed are intuitively meaningful, they do not require training for use, they are not easily forgotten, they are phonetically dissimilar, and there is virtually no possibility of inadvertent actuation.

Table 12. Suggested Vocabulary for Speech Controller

Word	Primary Function
Roll	Denotes roll rotation
Pitch	Denotes pitch rotation
Yaw	Denotes yaw rotation
X	Denotes translation along X axis
Y	Denotes translation along Y axis
Z	Denotes translation along Z axis
Plus	Denotes positive direction of motion
Minus	Denotes negative direction of motion
Stop	Removes all commands from ACS
Cage	Places ACS in synchronous mode

Command Code

It is clear that the astronaut's commands to the speech controller comprise an artificial language, one having its own rules of syntax. The language is not wholly artificial, however, since a tenuous (but psychologically important) connection with conventional language is maintained through the use of familiar terms in their normal meanings. Just as the employment of familiar terms makes the use of the artificial language easier, so also will the adoption of a rational, easily understood sentence structure help to make the language serviceable. Three valuable criteria for use in constructing a good artificial language are:

- Preciseness. The language must denote, clearly and directly, what its user intends.

- Conciseness. The language must express a command without superfluous or elaborative elements. This criterion is particularly important in the present application.

- Simplicity. The rules of sentence construction must be few in number, uncomplicated, and easy to apply.

Several possible syntactical approaches, based on the above criteria, are now considered. Referring back to Table 10, it can be seen that the five elements that must be inserted into every maneuver command to the ACS are:

- The maneuver desired
- The direction of the maneuver
- The speed (or acceleration) of the maneuver
- The time of execution
- The duration of the maneuver

Two possible methods of command construction suggest themselves. The first is exemplified by the command,

"Roll, plus-plus"

by which the astronaut would establish a roll to the right at low speed. In this case, "roll" designates the maneuver, the first "plus" establishes the direction (and the precision speed unless followed by another "plus"), and the second "plus" signifies low speed. Execution is performed upon completion of voice inputs to the controller.

There is much to recommend the above syntactical pattern: it meets the general requirements for preciseness, conciseness, and simplicity. The command is clear, brief, and efficient. One possible objection concerns the effectiveness of the astronaut's control over the time of execution. The utterance of a term like "plus-plus" (to command the low speed) or "plus-plus-plus" (to command the highest speed) does not permit as accurate a pinpointing of the time of execution as would be possible with a single word.

The above objection can be overcome by the second form of command construction to be considered. This method is illustrated by the command,

"Roll-roll, plus"

by which the astronaut would establish the same command as in the first example -- a roll to the right at low speed. Here the first "roll" designates the maneuver; the second "roll", together with the first, determines the speed, and the "plus" establishes the direction and the time of execution. This type of command has the same advantages of preciseness, conciseness, and simplicity as first type, and, in addition, permits accurate pinpointing of the time of execution, since the execution command (consisting of the last word uttered) can be given at precisely the desired moment. This method, then, would seem to be preferable to the first method.

Thus far, nothing has been said about the kind of commands needed to control the duration of the maneuver. Duration can be controlled in one of two ways:

- A rotational or translational rate, once established, can be maintained by silence on the part of the astronaut. At the desired moment, the astronaut can terminate the maneuver with a single "stop" command.

- The maneuver can be sustained by having the astronaut repeat the execution command ("plus" or "minus") at fixed intervals. Repetition intervals of one second seem reasonable. It is highly unlikely that a maneuver (a rotational rate or a translational acceleration) will be sustained longer than 10 seconds, and the necessity for the astronaut to repeat the execution command up to 10 times does not appear to impose an undue burden upon him. The advantage of this method of command continuation is that it is failsafe: if for any reason the astronaut should fall silent -- because of preoccupation with his task, confusion, accident, etc. -- rotational and translation commands to the ACS are automatically removed.

The reasons why maneuver duration times are expected to seldom, if ever, be 10 seconds long is explained below with reference to Table 13. In this table, the effective ΔV for translation commands and the effective $\Delta\theta$ for rotation commands are given for 1- and 10-second durations. Under the "10-Second Duration" column, the following facts emerge:

- Using high-thrust translation, a ΔV of nearly 40 fps can be achieved in 10 seconds. Given the modest distances the extravehicular astronaut will be traversing, this ΔV capability seems more than adequate.

- Using low-thrust translation, a ΔV of about 3 fps can be attained in 10 seconds. This same speed can be obtained with a 1-second command at high thrust. It is unlikely, therefore, that translation commands longer than 10 seconds would occur at low thrust.

- A 10-second high-rate rotation command will result in a $\Delta\theta$ of 200 degrees. It seems clear that a $\Delta\theta$ of greater than 180 degrees can be accomplished more efficiently by "going the other way".

- A low-rate (3-deg/sec) rotation command lasting 10 seconds will result in a $\Delta\theta$ of 30 degrees. It seems probable that an astronaut desirous of attaining a large attitude change (20 degrees or greater) would use the high-rate rotation command for an extended period of time.

Table 13. Maneuver Capability - One- and Ten-Second Command Duration

Mode	Maneuver Capability - Effective ΔV or $\Delta\theta$	
	Single Command (1-second duration)	Sustained Command (10-second duration)
Translation - High Thrust	X: 3.8 fps Y-Z: 3.0 fps	X: 38 fps Y-Z: 30 fps
Translation - Low Thrust	X: 0.29 fps Y-Z: 0.22 fps	X: 2.9 fps Y-Z: 2.2 fps
Rotation - High Rate	20 deg	200 deg
Rotation - Low Rate	3 deg	30 deg
Rotation - Precision Rate	0.15 deg	1.5 deg

- The precision rate of rotation is used for the alignment of optical equipment. Since final alignment error probably would seldom exceed one degree, it is highly unlikely that command durations as long as 10 seconds would be needed.

In view of the short maneuver duration times expected and the inherent failsafety of the technique, command repetition is considered preferable to any other method of sustaining a maneuver.

Table 14 summarizes the various types of commands the astronaut can use to start, sustain, and stop rotational and translational maneuvers. It can be seen that there is only one way to start a maneuver and one way to sustain it. The uniqueness of the commands required for these phases of the maneuvers is a safeguard against inadvertent actuation, and a guarantee of consistent, easily understood operating procedures. It can also be seen that a maneuver can be terminated by a "stop" command and by silence, the latter method constituting the failsafe feature discussed previously.

Table 14. Examples of Types of Commands for Various Phases of Maneuvers

Maneuver	Start	Continuous Command	Stop (Attitude Hold, Zero Acceleration)	Synchronous Mode (Work Configuration)
Rotation	"Roll-roll, plus"	"Plus, plus, plus..."	1. Silence 2. "Stop"	"Stop-Cage"
Translation	"X-X, plus"	"Plus, plus, plus..."	1. Silence 2. "Stop"	"Stop-Cage

Continuous Command

The general principle established in the foregoing discussion, that silence on the part of the astronaut removes all maneuver commands from the ACS, can be restated as follows: Silence implies zero translational acceleration and zero rotation. Under these conditions, there will be no rotation and no translational velocity changes. A spoken command implies a change from the condition of no rotation and no translational acceleration.

The rules governing the establishment of continuous command conditions can be summarized as follows:

- In attitude, continuous utterances command continuous rotation. Silence commands constant attitude.

- In translation, continuous utterances command continuous acceleration. Silence commands constant speed (a special case of which is zero speed relative to the astronaut's mother vehicle).

Multi-axis Control

It is clear that the method of vocally addressing the speech controller outlined in the preceding paragraphs permits maneuvering in only one axis at a time. If the astronaut addresses commands to the controller establishing, for example, a low-speed yaw to the right, and maintains this maneuver by uttering a succession of "plus" words, the utterance of other rotational or translational commands is precluded. On the other hand, if the astronaut terminates the yaw maintenance commands in order to make other commands, the yaw maneuver ceases.

This exclusionary characteristic of the controller, far from being a handicap to the astronaut, is a distinct advantage, for the following reasons:

- The simplified operating procedure resulting from sequential axial control is compatible with the most accurate method of attitude correction: one axis is controlled at a time at the appropriate speed for that axis.

- The "stop" command might have an unwanted meaning if issued during simultaneous multi-axis maneuvers. As defined, the command would be effective in all axes simultaneously; final adjustments in alignment would be made on a single-axis basis anyway.

- It is believed that single-axis sequential control is less confusing to the astronaut and will result in fewer overshoots and less fuel waste.

Deadband Control

The ACS is provided with two deadbands, a wide deadband of ± 10 degrees that is used during most normal operations, and a narrow deadband of ± 0.8 degree that is used during telescope pointing. Since it will be necessary during extra-vehicular operations for the astronaut to select the deadband appropriate to the task being performed, provisions are made for the controller to recognize two commands: "stop-plus", by which the astronaut can obtain wide deadband limits in all body axes, and "stop-minus", by which the astronaut can obtain narrow deadband limits. The use of words from the existing vocabulary ("stop", "plus", and "minus") avoids an unnecessary expansion of the voice recognition facilities.

Since the use of narrow deadband limits is invariably associated with precision rates of rotation, provision has been made to obtain the narrow limits automatically whenever the precision rates are called for. Thus, for telescope pointing purposes, the astronaut can obtain narrow limits when commanding a precision rate or, when in a steady-state (zero rotation) condition, by commanding "plus-minus". When the ACS is placed in the caged mode, the narrow limits are automatically removed and the system reverts to the wide limits.

VOICE CONTROLLER MECHANIZATION

Vocabulary

It has been shown that the astronaut must be able, through the use of verbal commands, to exercise control over a total of 36 maneuver and mode selection possibilities. It was also shown that all 36 commands can be formulated in terms of 10 words, since some aspects of the commands (e.g., speed) can be expressed by use of certain coding techniques. It is clear that vocabularies of various sizes are possible, depending upon the amount of encoding used. In the following discussion, 13 different types of vocabularies are analyzed and evaluated in an attempt to determine an optimum size.

With a vocabulary consisting of 16 natural language words, all rotational, translational, and mode selection commands can be uttered with no repetition or coding of any kind (e.g., "yaw, right, fast"). Thus, 16 words comprise the largest voice-controller vocabulary needed to provide control over the complete set of 36 maneuver and mode variables.

Other vocabularies, ranging in size from 15 down to 8 words, can be constructed by coding one or more components (maneuver, direction, or speed) of the command. All of these vocabularies employ words in the natural language (e.g., "roll", "left", "fast", "plus", etc.). Several of the vocabularies contain the terms "X", "Y", and "Z", which, while not common, are familiar to pilots and astronauts by virtue of their close association with aerodynamic terminology.

A radical innovation -- the use of artificial sounds instead of natural language words -- can be used in one-word or two-word vocabularies. The "dit-dah" motif may be used to represent sounds in these pulse code systems, or other sounds, having better recognition features and less likely to occur in normal communication, may prove superior.

Duration of Command Utterance -- For the 16-word vocabulary -- the direct language vocabulary -- all rotational commands are accomplished with three words, all translational commands with two words, and all mode switching commands with one word. By assigning an average time value of 0. 3 second for each word uttered, and 0. 3 second for each pause between words, the time required for utterance of the longest and shortest commands can be estimated, as shown in Table 15. It can be seen that as the number of words available decreases and the amount of encoding increases, more time is required to complete a command utterance.

Table 15. Summary Tabulation of Voice-Controller Vocabularies of Different Sizes

Table No.	Type of Vocabulary	No. of Words	Estimated Time for Commands (sec)	
			Min	Max
1	Complete, Direct Language	16	0. 3	1. 5
2	Codified Limit Commands	14	0. 3	1. 5
3	Codified Direction Commands	15	0. 3	1. 5
4	Codified Direction and Limit Commands	13	0. 3	1. 5
5	Codified Speed Commands	13	0. 3	2. 1
6	Codified Speed and Limit Commands	11	0. 3	2. 1
7	Codified Direction and Speed Commands	12	0. 3	2. 1
8	Codified Direction, Speed, and Limit Commands	10	0. 3	2. 1
9	Codified Maneuver, Direction, and Speed Commands	10	0. 3	2. 4
10	Codified Maneuver, Direction, Speed, and Limit Commands	8	0. 3	2. 4
11	Three-Word Pulse Code	3	0. 3	2. 7
12	Two-Word Pulse Code	2	0. 6	2. 7
13	One-Word Pulse Code	1	1. 5	3. 0

Evaluation of Vocabularies -- Three important disadvantages preclude the adoption of one of the pulse codes. First, the "words" (i. e., the artificial sounds) would of necessity be highly unusual and therefore would be difficult to remember and use.

The second reason that militates against the use of pulse codes is that a command utterance is heavily time-dependent. The very small number of vocabulary words requires that they be combined into repetitive sequences to form commands, with the pauses between portions of the command being highly significant. Thus, the timing of command utterances, or portions thereof, is extremely important to their being interpreted correctly by the speech-recognition system. This timing function puts an additional burden on the astronaut in terms of the training and skill required, and adds significantly to the complexity of the voice controller logic circuitry.

The third disadvantage of the pulse code vocabulary has already been pointed out in connection with Table 15. Because of the excessive amount of coding required, a longer time is required to formulate a full command than is necessary with natural language vocabularies.

An evaluation of the remaining ten possible voice-controller vocabularies, and the selection of a preferred one, is difficult since some of the criteria needed for such a selection are not available. From a human factors standpoint, the 16-word vocabulary is doubtless the best:

- All commands are in the natural language
- They are concise, precise, and simple
- Virtually no training would be required
- There is extremely small likelihood of forgetting

However, other major factors such as system size, weight, and cost must be considered. A system designed for very small vocabularies pays a heavy penalty in extreme circuit complexity, whereas a system designed for large vocabularies pays a penalty in word sensor complexity. Thus, the optimum system seems to lie somewhere in the middle range of the curve. Taking all factors into account (human factors considerations, word recognition system complexity, and logic circuit complexity), a vocabulary of 10 words offers the most advantages and fewest disadvantages of any other:

- It uses meaningful words from the natural language.
- The vocabulary is large enough to permit the construction of whole commands without excessive coding and to avoid extreme circuit complexity.
- The vocabulary is small enough to avoid an unduly large speech recognition system.

On the basis of the foregoing evaluation, the 10-word vocabulary of Table 16 was selected as a basis for further development.

Table 16. Vocabulary With Codified Direction, Speed, and Limit Commands

Type of Control	Maneuver or Mode Command	Direction Commands		Speed Commands		
		Plus	Minus	Fast	Slow	Precise
Rotation						
Roll	Roll	Plus	Minus	Roll^3*	Roll^2*	Roll
Pitch	Pitch	Plus	Minus	Pitch^3	Pitch^2	Pitch
Yaw	Yaw	Plus	Minus	Yaw^3	Yaw^2	Yaw
Translation						
X	X	Plus	Minus	X^2	X	
Y	Y	Plus	Minus	Y^2	Y	
Z	Z	Plus	Minus	Z^2	Z	
Mode						
Stop	Stop					
Cage	Cage					
Wide	Stop-Plus					
Narrow	Stop-Minus					

Roll	X	Plus	Stop	Total Words: 10
Pitch	Y	Minus	Cage	
Yaw	Z			

*Roll^3 (pitch^3, etc.) = "roll-roll-roll" ("pitch-pitch-pitch", etc.)
Roll^2 (pitch^2, etc.) = "roll-roll" ("pitch-pitch", etc.)

Speech Recognition Devices

To accurately gauge current state of the art in the speech recognition field, a specification was written (based on Section IV of Appendix A of this report) describing a voice recognition device for a breadboard voice controller. The specification was given to all firms who had indicated an interest in the speech recognition field. Four companies replied to the specification, setting forth their techniques for speech recognition.

While the techniques of speech recognition varied somewhat between vendors, there was general agreement on the proper approach to certain problem areas. The following general statements define the broad areas of agreement among the companies solicited:

- For a small vocabulary (such as that proposed for the AMU-ACS) a fairly simple recognition system would suffice.
- The astronaut should be trained to speak slowly and articulate clearly.
- Speech recognition is less difficult for highly articulated speech (again, such as that proposed for the AMU) than for fluent speech.
- If natural words are used instead of artificial words, a special execution command is recommended. In any case, polysyllabic command words should be used because they contain more recognition features.
- The recognition and execution of inadvertently inserted commands is a problem that can be minimized if:
  1. The logic circuitry requires that words comprising a command be inserted in a prescribed sequence.
  2. The input logic has a time delay reset feature so that if a command is not completed within a small time period, all words are erased.
  3. An exotic word is used for "execute".
- The probability of recognition errors occurring will greatly diminish if the voice controller can be tailored to a specific individual.

Each of the four companies replying offered a different approach to the detection and recognition of voiced sounds. None of the methods have been developed to the stage where off-the-shelf equipment is available. All of the approaches start with the realization that spoken words are made up of phonemes, or different sounds, occurring in a particular order. Word recognition consists of detecting the types and timing or order of the phonemes as they occur. Variations in the approaches are basically in the types of phoneme detectors used.

Output Logic

The AMU voice controller logic, shown in Figure 10, decodes the voice recognition unit outputs and generates the specific discrete commands to the ACS. The voice recognition unit will recognize 10 words and supply a pulse on a separate line for each of these words. Two to four words in proper sequence are required to generate one of the 32 control commands out of the logic.

A typical voice command sequence would be "yaw-yaw-yaw-plus" to generate a yaw at high speed in a positive direction. Flip-flops f_0 and f_1 count the number of "yaw" words uttered to determine the desired speed. The true outputs of f_0, f_1, and f_{12} are gated to generate the command level output. To sustain motion, the astronaut will be required to repeat the word "plus" at a rate of once per second as a form of dead man cutout. Flip-flops f_{14} and f_{15} count 1-second pulses and reset f_{12} at 1 second if another "plus" word has not occurred. The 1-second time interval can be increased to 2 or 3 seconds by gating other combinations of f_{14} and f_{15} outputs Rotation in pitch and roll and translation in X, Y, Z directions are decoded in a manner similar to yaw commands. The word "stop" uttered at any time removes all maneuvering commands and clears the system for new commands.

The phrases "stop-plus" and "stop-minus" are used to select wide and narrow deadband limit commands, respectively. The word "stop" is uttered to clear the maneuvering commands and set f_{17}. The phrase "stop-plus" then sets f_{18} and f_{12}. These flip-flops are gated together to set f_{19}, the deadband select flip-flop. The phrase "stop-minus" resets this flip-flop. The word "cage" generates a command to place the gyros in an attitude synchronous mode of operation and selects wide deadband limits. Any maneuvering command removes the cage command.

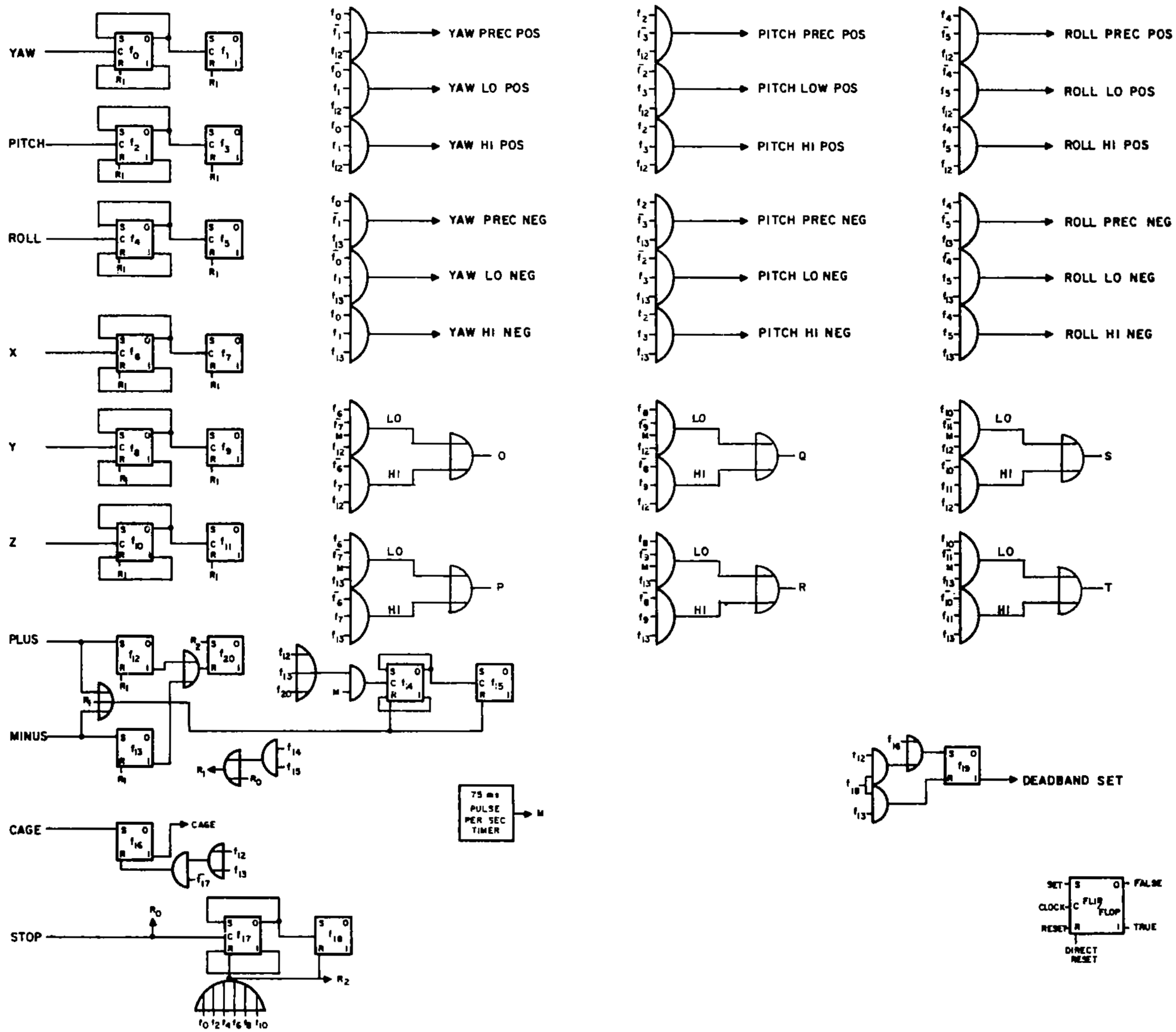

Figure 10. AMU Voice-Controller Logic

Positive levels provide the normal "on" commands for all outputs except the translation O, P, Q, R, S, T low-speed commands. O, P, Q, R, S, and T are the translation positive and negative commands for each of the three axes (see Figure 10). The output here consists of a 75-millisecond duration positive pulse occurring once per second while this command is in effect. The output of a timing circuit is gated with these commands to generate the pulse output.

All maneuver command sequences have to be spoken in a 3-second interval or a reset is generated and the partial command is removed. The first word in a command sequence sets f_{20}, enabling the two-bit counter f_{14} and f_{15} to count once-per-second pulses from the timer. If the counter reaches 3 before a "plus" or "minus" word occurs, a reset is generated to clear all maneuver command flip-flops. A time limit on the command sequence reduces the probability of unintentional words generating undesired commands.

The main power supply in a final design for the AMU will be 28 volts dc from rechargeable batteries. To generate the 6 volts dc needed to drive the voice controller logic, a simple zener diode and resistors can be used for regulation and voltage dropping. The voice recognition unit will use both the 28 volts dc from the main supply and the 6 volts dc from the logic section.

COMPUTER SIMULATION OF VOICE CONTROLLER

An empirical investigation was undertaken to establish the feasibility of controlling the attitude control system by means of the voice. Accordingly, a computer simulation of the voice-operated controller was set up. Its construction and operation are described in the following paragraphs. The simulation did not include a voice-recognition mechanism, since none was readily available; voice decoding was done by a "human servo", described below. While the data obtained from the simulation was insufficient to permit definite conclusions to be drawn concerning the quality of voice control, preliminary results indicate that a voice controller is practicable.

Equipment

The following items of equipment comprised the voice control simulation setup:

- Reeves analog computer (REAC) -- 21 amplifier
- Hewlett-Packard low-frequency oscillator
- DuMont cathode-ray tube (5 inch)
- Sanborn recorder (4 channels)

The components were arranged as shown in Figure 11, which is a block diagram of the experiment. The block labeled "human servo" requires a word of explanation. Since an operating voice-recognition device was not available, a human substitute was used -- a person who received the voice commands of the subject and transduced them into control inputs. The human servo exercised no discretionary judgment, but merely responded, as consistently and uniformly as possible, to the verbal instructions given him by the subject.

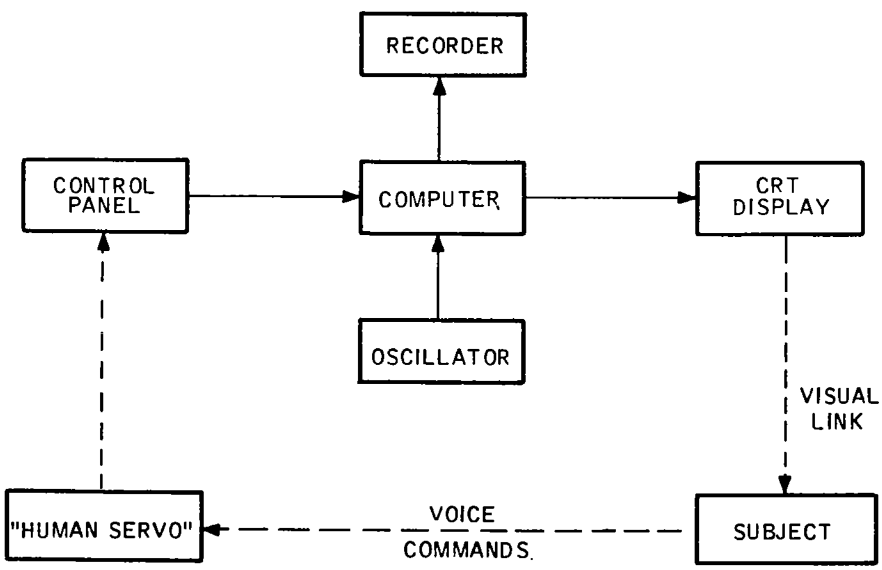

Figure 11. Computer Simulation of Voice Controller

The simulation operated as follows: The subject watched the cathode-ray tube (CRT) on which a spot represented the target toward which he was translating. To change his attitude or range (to make the spot move or grow), the subject uttered appropriate verbal commands. These were interpreted by the human servo and inserted into the computer through suitable switches. The computer transmitted these commands to the cathode-ray tube, thus closing the control loop back to the subject. The circuit diagrams describing the several computer circuits are shown in Figures 12 through 15.

Attitude Control Problem

This problem simulated the action of the astronaut in aligning the crosshairs of a sighting telescope on a rendezvous target in the presence of an ACS limit cycle. To simulate the limit cycle, the spot was made to oscillate in the vertical and horizontal directions (representing the pitch and yaw axes, respectively) with an amplitude corresponding to ±0.8 degree and at a frequency of 0.2 cps. The subject was to align the crosshairs on the target (place the arbitrarily offset spot on the scope center by issuing verbal commands to the "human servo"), and to keep the target within a ±1 degree square. Individual subjects were scored (after a moderate amount of practice) on the basis of fuel consumption and time.

Three types of tests were run during the attitude control study. First, commands were couched in direct language terms and in natural language coded terms. (Terms were used that were appropriate to the simulation problem, such as "right", "left", "fast", and "slow".) The difference between these two types of vocabularies is presented in Table 17, where for illustrative purposes the command shown will drive the spot leftward at the higher of two available speeds. Second, an established attitude rate was sustained in each of two ways: by repeating the last word of the command at the rate of once per second, in which case the imposition of silence terminated the maneuver, and by maintaining silence during the maneuver, in which case the termination was effected with the word "stop". The difference between these two

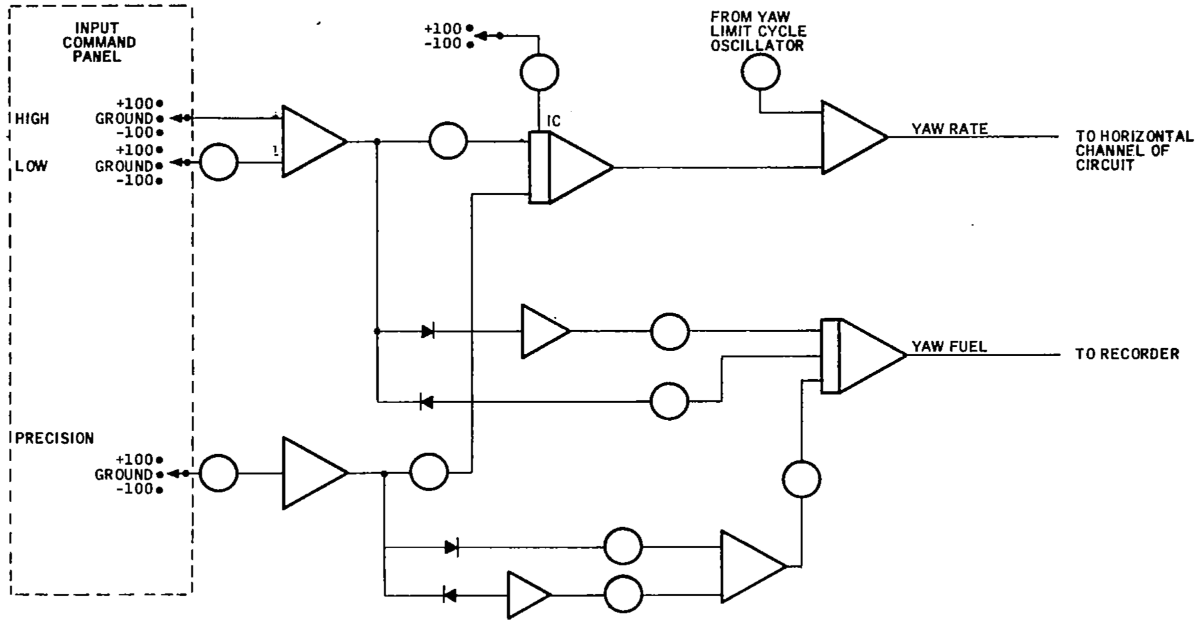

Figure 12. Yaw and Yaw Fuel Computer Circuit

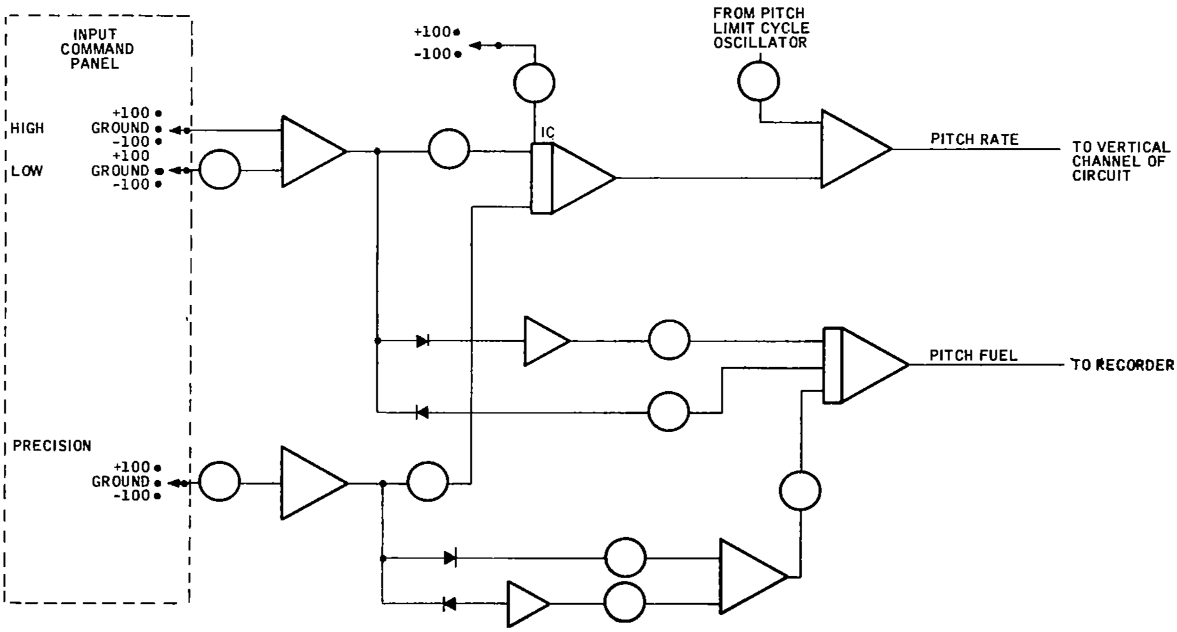

Figure 13. Pitch and Pitch Fuel Computer Circuit

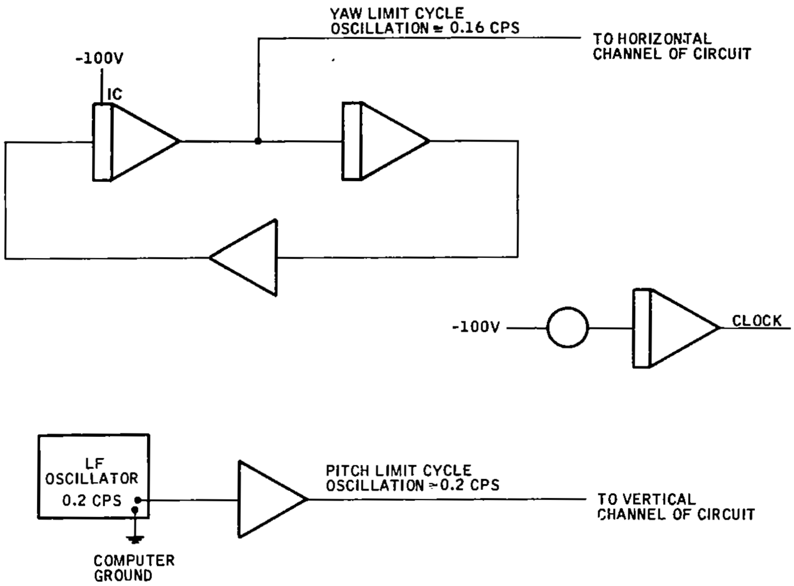

Figure 14. Limit Cycle Computer Circuit

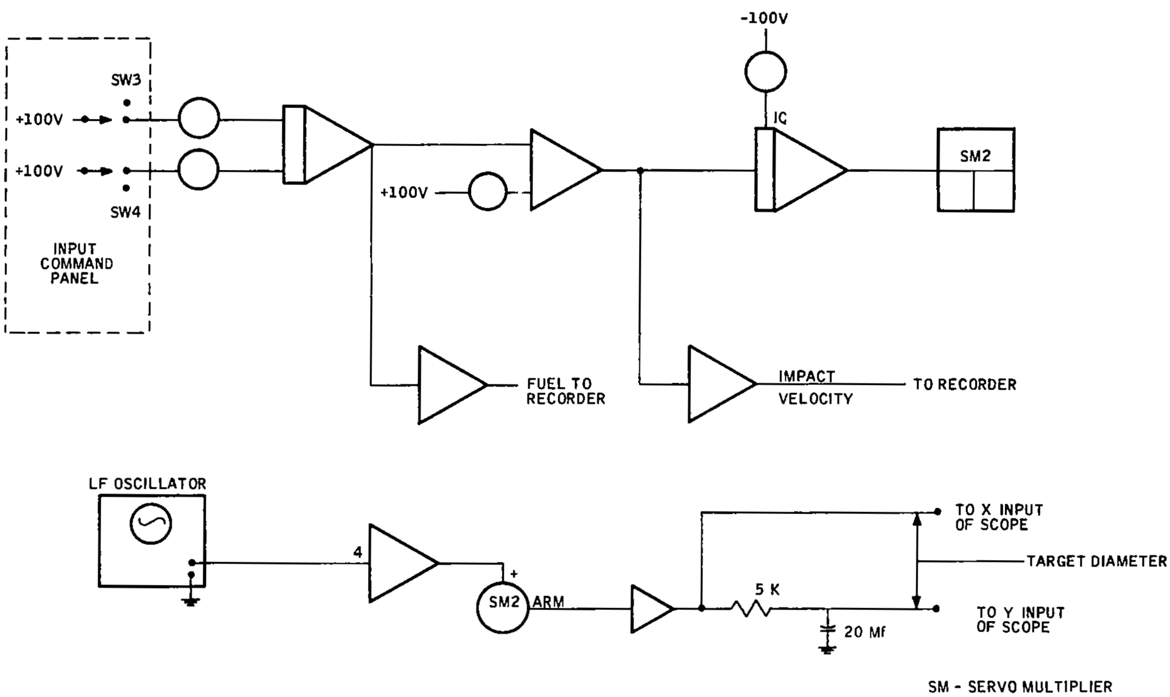

Figure 15. Translation Computer Circuit

types of maneuver maintenance techniques is also shown in Table 17. The third type of test used during the attitude control study employed first a ±1 degree circle at the center of the scope into which the spot was driven, and then a ±2 degree circle (total widths 2 degrees and 4 degrees, respectively).

Table 17. Examples of Commands for Attitude Control Simulation Study

Method of Maneuver Maintenance	Direct Language Command	Coded Language Command
Silence	"Left, Fast"	"X-X, Minus"
Repetition	"Left, Fast, Fast . . ." etc.	"X-X, Minus, Minus . . ." etc.

Three parameters were recorded for each trial: time to completion, simulated fuel consumption, and final error. The results of the attitude control study, averaged over all subjects and trials for each test, are shown in Table 18.

Table 18. Results of Attitude Control Simulation Study

Type of Command	Target Size (deg)	Time (sec)	Fuel Consumption (normalized)	Error (deg)
Direct, Repetitive	±1 ±2	16.5 11.4	1.11 1.04	0.8 1.2
Direct, Silent	±1 ±2	15.0 6.3	1.12 1.00	0.6 0.5
Coded, Repetitive	±1 ±2	18.6 9.8	1.08 1.04	0.8 0.8
Coded, Silent	±1 ±2	19.5 7.0	1.04 1.00	0.8 0.6

The data revealed considerable variation in performance, due partially, no doubt, to the effects of learning in any given subject. Although an effort was made to minimize this effect by providing the subjects with practice, the effect could not be eliminated completely without use of excessively long practice sessions. A second source of variation in the performance data was the differences between subjects. This effect can be reduced by using a large number of subjects. For these experiments six subjects were used, and the results represent the averages for those subjects.

Simultaneous control of the spot in two axes was too difficult to be practicable. This difficulty was due at least in part to the structural limitations of the experiment: a spot traveling at a rate of 3 degrees per second across a five-inch cathode-ray tube could not be adequately controlled in both the horizontal and vertical directions simultaneously. The difficulty was also due in part to the need for using a "human servo"; the added response time introduced lags in the system which probably would not be present in a voice controller. In space, simultaneous control over large angular changes in more than one axis may be possible, but since nothing is saved in fuel consumption and the possibilities of errors arising out of confusion and haste are increased, sequential rather than simultaneous control is recommended.

The data of the study is inconclusive regarding the superiority of the direct form of command ("Right, fast") or the natural language coded form of command ("X-X, plus"). The differences between the two methods of command, determined by the criteria of time required, fuel consumption, and final error, are small and do not appear to be significant. Similarly, the differences between the repetitive method of rotational maintenance ("Left, fast, fast. . . ") versus the silent method ("Left, fast". . . "Stop") were very small. A small advantage was seen for the latter technique, in that it was slightly easier for the subject to pinpoint the moment of stopping accurately by using the word "stop" than with silence. Since, however, the repetitive technique is greatly preferable from a failsafety standpoint in translation maneuvers, it is recommended for rotational maneuvers also in order to make the verbal inputs for each type consistent. Furthermore, in the operational situation, the "stop" command can still be used with the repetitive technique.

The data of Table 18 shows that attitude changes can be accomplished more easily using the larger of two targets. In every case, increasing the target size permitted the subject to drive the spot to the desired area more quickly, but, interestingly enough, the final errors did not increase. This was probably due to the inherent accuracy with which a high-speed maneuver can be terminated. Given a little practice, a subject can terminate a high-speed rotation just about as well as a low-speed rotation. This test established that a rotational maneuver can be performed more quickly, and just as accurately, if the final attitude can fall between wide limits than if it must fall between narrow limits.

Translation Control Problem

This problem required the subject to translate toward and to dock upon a target. The decrease of range between subject and target was simulated by the growth of the spot on the face of the CRT. The initial conditions of the problem placed the subject in forward velocities corresponding to 8, 12, and 16 feet per second, and a range of 50 feet. By issuing verbal commands, the subject could apply retro-thrust in order to decelerate to zero relative velocity just as he arrived at the target. The moment of docking was indicated by the target diameter reaching a certain value marked on the scope. Scoring was done on the basis of fuel consumption, time, and impact velocity.

Two types of tests were run during the translation control simulation study. In one, verbal commands were given in direct language. In the other, speed commands were coded. The differences between the two types of commands are shown in Table 19. As can be seen from the table, all commands were given in the repetitive mode; i.e., the acceleration was maintained just as long as the execution command was repeated at one-second intervals. The justification for this type of command is again that it is failsafe: if the astronaut falls silent, the acceleration commands to the ACS are removed. Trials were conducted using simulated approach velocities of 8, 12, and 16 fps.

Table 19. Commands for Translation Control Simulation Study

Translation Maneuver	Direct Language Command	Coded Language Command
Forward, Slow	"Forward, slow, slow..."	"X, plus, plus..."
Forward, Fast	"Forward, fast, fast..."	"X-X, plus, plus..."
Backward, Slow	"Back, slow, slow..."	"X, minus, minus..."
Backward, Fast	"Back, fast, fast..."	"X-X, minus, minus..."

Results of the translation simulation study are shown in Table 20. As was the case in the attitude control study, there is little difference between the direct and coded forms of command address. Neither type appears to have a marked superiority over the other. Therefore, a choice betwen them will have to be made on other grounds, e.g., amount of training required.

Table 20. Results of Translation Control Simulation Study

Approach Velocity	Command Vocabulary	Time (sec)	Fuel Consumption (normalized)	Impact Velocity (fps)
8 fps	Direct	24.7	1.1	0.8
	Coded	22.2	1.0	0.7
12 fps	Direct	17.0	1.3	1.2
	Coded	18.0	1.4	0.6
16 fps	Direct	14.0	1.3	2.7
	Coded	13.6	1.2	2.0

Summary of Results

Results of the voice-control simulation studies are summarized below:

1. There was greater consistency between trials conducted on one subject than between subjects.

2. Simultaneous control in two axes proved unfeasible within the constraints of the simulation.

3. No advantage was shown for either the direct command vocabulary or the one in which speed commands were coded.

4. It appeared slightly easier to maintain an attitude maneuver by silence, and to terminate it by uttering "stop", than by using the repetitive command technique. This advantage is not considered significant, however, and is far outweighed by the failsafety inherent in the repetitive technique.

5. Adequate attitude control appeared feasible with rates used, which corresponded to 3 and 0.15 degrees per second.

6. Adequate translational control was achieved using approach velocities of 8, 12, and 16 feet per second. As might be expected, higher approach velocities resulted in shorter docking times. Differences in fuel consumption were not significant. Slightly lower impact velocities were achieved with initial velocities of 8 feet per second.

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SECTION V

ATTITUDE CONTROL SYSTEM INVESTIGATION

The Attitude Control System investigation comprised the following steps:

- Determination of requirements
- Survey of attitude control systems
- Selection of a system
- Construction of mathematical models for simulation
- Determination of parameters
- Verification of performance

ACS REQUIREMENTS

The ACS was required to have 360° command capability in each axis so that the astronaut could orient himself in any direction. This capability was required at three levels: 20°/sec, 3°/sec and 0.15°/sec. To some extent these levels were arbitrary. The highest level was selected so that large maneuvers would be completed quickly. The lowest level was selected to provide an extremely fine trim on attitude for the alignment of optical devices.

Two levels of translational acceleration were to be provided. The larger of these was full thrust for the duration of the command. The lower level provided full thrust for 75 ms. each second of command duration.

To permit the astronaut to re-orient "by hand" at the work site or home vehicle, a synchronous mode is required. The gyros are caged by the torquer amplifiers and jet actuation power is removed from the electronics.

During the rendezvous portion of the mission, satisfactory error correction can be made if the attitude limit cycle is kept within ± 1° in yaw and pitch. While the rendezvous problem imposes no limitation on roll attitude control, roll attitude cannot be permitted to vary over excessively wide limits or the astronaut may confuse pitch and yaw errors. The roll limit cycle is restricted to ± 5°.

As these stringent limits are unnecessary for performance of work tasks the attitude limits were opened up to ± 10° in all three axes.

A maximum permissible attitude rate during command attitude changes of 40°/sec (Reference V-1) was established to avoid discomfort and possible disorientation.

ATTITUDE CONTROL SYSTEMS

Systems

Characteristics of several Attitude Control Systems were evaluated. Only those systems which utilize gyroscopes to control on-off reaction jets through electronic logic circuitry were included. Results are summarized in Table 21.

Table 21. Attitude Control Systems (Estimated Characteristics)

System No.	Modes of Control	Gyros	System Accuracy	Normalized Volume*	Normalized Weight*	Normalized Power*	Normalized Cost*	Mechanization	Controller Input Requirement
1	Attitude Hold Attitude Precession	Wide angle miniature integrating gyros	Within 0.5 deg/hr on attitude hold Within 5 per cent on attitude precession	1.0	1.0	1.0	1.0	Networks for damping Attitude gyros for attitude reference	Attitude precession command (equivalent to attitude rate command but with attitude hold at command termination)
2	Attitude Hold Attitude Precession and/or Attitude Rate	Wide angle miniature integrating gyros Miniature rate gyros	Within 0.5 deg/hr on attitude hold Within 5 per cent on attitude precession Within 5 per cent on rate command	1.2	1.3	1.1	1.2	Rate gyros for damping Attitude gyros for attitude reference	Attitude precession command and/or Attitude rate command (option of including attitude hold at command termination)
3	Integrated Attitude Rate Attitude Rate	Miniature rate gyros	About 18 deg/hr drift on integrated attitude rate Within 5 per cent on attitude rate command	0.7	1.0	0.2	0.6	Rate gyros for damping Integrated attitude rate for attitude error generation	Attitude rate command (option of including integrated rate error at command termination) and/or Integrated rate precession

*Per system - nonredundant mechanization

System 1 is the minimum complexity system which will meet the requirement for holding attitude within 1 degree of initial reference for the coast phase during rendezvous.

Control Techniques

Among the space vehicle control techniques which have received attention at Honeywell in recent years, the most prominent are:

1. Rate feedback
2. Orbit mode
3. Pulse width and pulse rate modulation
4. Derived rate
5. Pseudo-rate feedback

Rate feedback by rate gyroscopes - the traditional control technique for airplane autopilots has two disadvantages in space vehicle application. These are high power consumption and high threshold. High threshold should probably present no difficulty in AMU control systems, since the contemplated accelerations and minimum impulses are rather high.

Orbit mode control uses a series of fixed pulse widths switched at fixed error angles. This technique is capable of producing very low residual rates and low propellant consumption at the cost of complex circuitry and large errors in the presence of disturbing torques.

Pulse width and pulse rate modulation techniques require some form of damping for stability. They offer the possibility of smaller error angles in the presence of disturbance torques, but the extreme complexity of the circuitry probably rules them out for AMU use.

The derived rate control technique uses a lead network in the signal input path to feed a rate plus attitude signal to the jet control amplifiers. Major disadvantages of this technique are noise sensitivity and saturation. Lead networks are sensitive to high frequency noise. Since the attitude signal will be generated as an AC signal, this imposes severe conditions on the ripple content of the signal demodulator. If ripple is reduced by simple lag filtering, the frequency response of the control system is degraded.

The pseudo-rate control technique offers perhaps the greatest simplicity and immunity to circuit parameter variations. In this system, a signal proportional to angular acceleration is lagged (pseudo-integrated) and summed with the input attitude to form a pseudo rate feedback. This system is not as simple as the derived rate compensation scheme, but is far less sensitive to noise. Experiments with the Honeywell air bearing table have shown the system to be capable of reducing limit cycle rates below 0.001 deg/sec (with sufficiently small minimum impulse).

Selection of a Control System and Technique

Of the control systems considered, these two met the accuracy requirements:

- Integrating gyros plus rate gyros
- Integrating gyros with networks for damping

The second system was selected as it offers the advantages of lower cost, weight, volume and power consumption.

When no translational thrust is present, the system requiring minimum propellant is a system which uses a minimum pulse to reverse the sign of the attitude rate at the maximum permissible excursion. When translational thrust is present, the pseudo rate circuit has the fewest disadvantages and provides adequate control. The system selected used a combination of the two techniques. As the attitude error increases from zero, a fixed pulse of 17 ms is used. If the error continues to increase, the boundary of the pseudo rate control is crossed. The pseudo rate control will then generate a restoring torque by turning on or off the appropriate jets. At this time a signal proportional to the restoring torque is applied to the pseudo-rate lag network whose output is summed with the attitude error signal. When the resultant signal is reduced below the predetermined set point, the restoring torque is removed. This reduction in the signal corresponds to a reduction in the attitude error and establishment of an attitude rate in the proper direction. In the absence of a disturbance torque, the attitude error is reduced within a predetermined deadband and the attitude rate is reduced enough to limit cycle between minimum pulses. In the presence of a disturbance torque, pseudo-rate control will control smoothly to some offset attitude, since no restoring torque will be available without an attitude error.

ANALYSIS

The necessary steps to ensure a working control system which meets the established requirements were:

- positioning and aiming the eight jets so that all control functions can be performed
- determination of which jets should be fired to produce proper response
- setting of the switching points of the pulse and pseudo rate control
- setting of the pseudo-rate gain and time constant

Determining the location and orientation of the thrust jets was largely a matter of "cutting and trying" until all requirements were met. After positioning and aiming of the jets were determined, it was necessary to find which combinations produced the desired control response.

The setting of switching points and gains is not this simple. The paper-and-pencil technique of phase-plane plotting can be used to study preliminary control system designs. Effects of delay and hysteresis can be accounted for simply. However, effects of tail-off, thrust rise, and inertial coupling cannot.

After preparing a few phase-plane plots using ideal reaction jet characteristics to obtain initial values for switching points, the remaining control system parameters were determined with the aid of the analog computer. For this purpose, it was necessary to generate a set of mathematical models.

One model was developed to account for the transport delay, thrust rise and tail-off features of reaction jets.

A single-axis rigid model was developed to determine the effects of gains and switching points with reaction jet nonlinearities accounted for.

A single-axis model with a linear spring at the hip joint was developed to study the interaction of flexibility at this joint with the control system.

A three-axis rigid model was developed to study the suitability of the evolved design in the presence of inertial coupling.

The results of the simulations may be found in this section.

Location and Orientation of Reaction Jets

With each jet oriented to provide a force along each of three axes and a moment about each of three axes, it is possible to provide translational and angular accelerations with eight jets. Consider that the jets are located at the corners of a uniform rectangular box and that they are aimed approximately along the diagonals of the box as in Figure 16. If the line of action of a jet does not pass through the center of mass then that jet will produce a moment around each of the principal axes of the box.

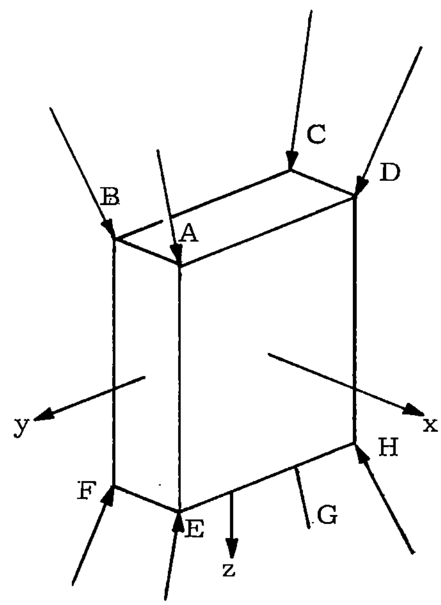


Figure 16. Jet Configuration

Operating all of the jets on one face (e.g., A, D, E, H) would produce a translational acceleration. Firing two jets on one edge (e.g., E and H) and the two jets diagonally opposite (B and C) could be used to apply a couple to the box about the Y-axis of Figure 16.

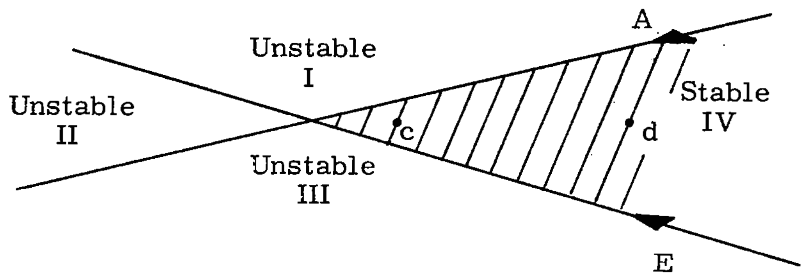


Figure 17. Simplified One-Axis System

The principal advantage of this system is its simplicity and associated reliability. Its main disadvantages are the change in control characteristics due to center of mass shift and poor propellant economy.

Figure 17 illustrates a simplified one-axis case. As long as the center of mass is in the shaded area, jet A will produce a counterclockwise angular acceleration and jet E a clockwise angular acceleration. However, the moment arms are longer when the center of mass is at d than when the center of mass is at c. Consequently, the angular accelerations produced by the jets will be higher when the center of mass is at d than when it is at c. If the center of mass moves into region I, both jets produce CW acceleration. A control system which relies on jet A to begin correction of a CW error will be unstable. If the center of mass moves into region III both jets produce CCW torque and the system becomes unstable. If the center of mass moves into region II, jet A will produce CW acceleration and jet E will produce CCW acceleration. A control system which relied on jet A to produce CCW angular acceleration and jet E to produce CW acceleration would be unstable.

Poor propellant economy in this system arises from three sources. First, the maximum angular accelerations are large because the jets must be sized to provide adequate translational acceleration and provision must be made for center of mass motion. Second, during translational acceleration, the jets are not aimed along the principal axes of the box.

In Figure 16, to produce acceleration along the -x axis, jets A, D, E, and H must be turned on. The component of force along this axis from each jet is less than the total force produced by the jet. Third, the application of translational acceleration when the center of mass is not precisely centered will result in an angular acceleration which must be corrected. The correction will produce an unwanted component of acceleration in another axis. For example, in Figure 16, -x translational acceleration is applied by turning on jets A, D, E, and H. If this were to cause a positive angular acceleration about the X axis, the required control activity (maintaining -x translational acceleration) would be to turn jets B and C on or to turn jets E and H off. In either case, the control activity would produce Z axis acceleration.

These disadvantages can be minimized by reducing the motion of the center of mass. Two methods of reducing this motion are to rigidize the suit so that postural variations are minimized, and to construct the backpack so that its center of mass is close to the man's center of mass.

In the model assumed in this study, the center of mass of the suited astronaut and the center of mass of the backpack are eleven inches apart. If jets located as shown in Figures 18 and 19 are aimed so as to produce the proper direction of angular acceleration for the extreme center of mass positions which can be produced by changes in backpack weight and postural variations, the translational acceleration along one axis is reduced to an extremely low level.

Extreme postural variations are under the control of the astronaut since they require a great deal of muscular effort. The backpack was assumed to be a box 36" x 18" x 8" with uniform mass distribution. However, it is not felt that the present backpack definition is sufficiently final to preclude use of one jet configuration or another. For these reasons and for simplicity, it was decided the eight jet configuration be used.

In order to select a location and orientation of the AMU reaction jets, it was decided to work with the USAF mean man and suit in the No. 1 position (see Figure 5). A 190-pound backpack 18 inches wide, 8 inches deep, and 36 inches high was also assumed, and the principal axes and principal moments of inertia were computed for this configuration. The principal axes relative to the backpack are shown in Figures 18 and 19. The principal moments of inertia are:

$$I_{xx} = 19.5 \text{ slug-ft}^2$$

$$I_{yy} = 22.4 \text{ slug-ft}^2$$

$$I_{zz} = 6.3 \text{ slug-ft}^2$$

It was desired to use 15-pound jets and find a location for them that would satisfy the following conditions:

- The translational acceleration along the principal axes in both the plus and minus directions should be about 0.1 g.

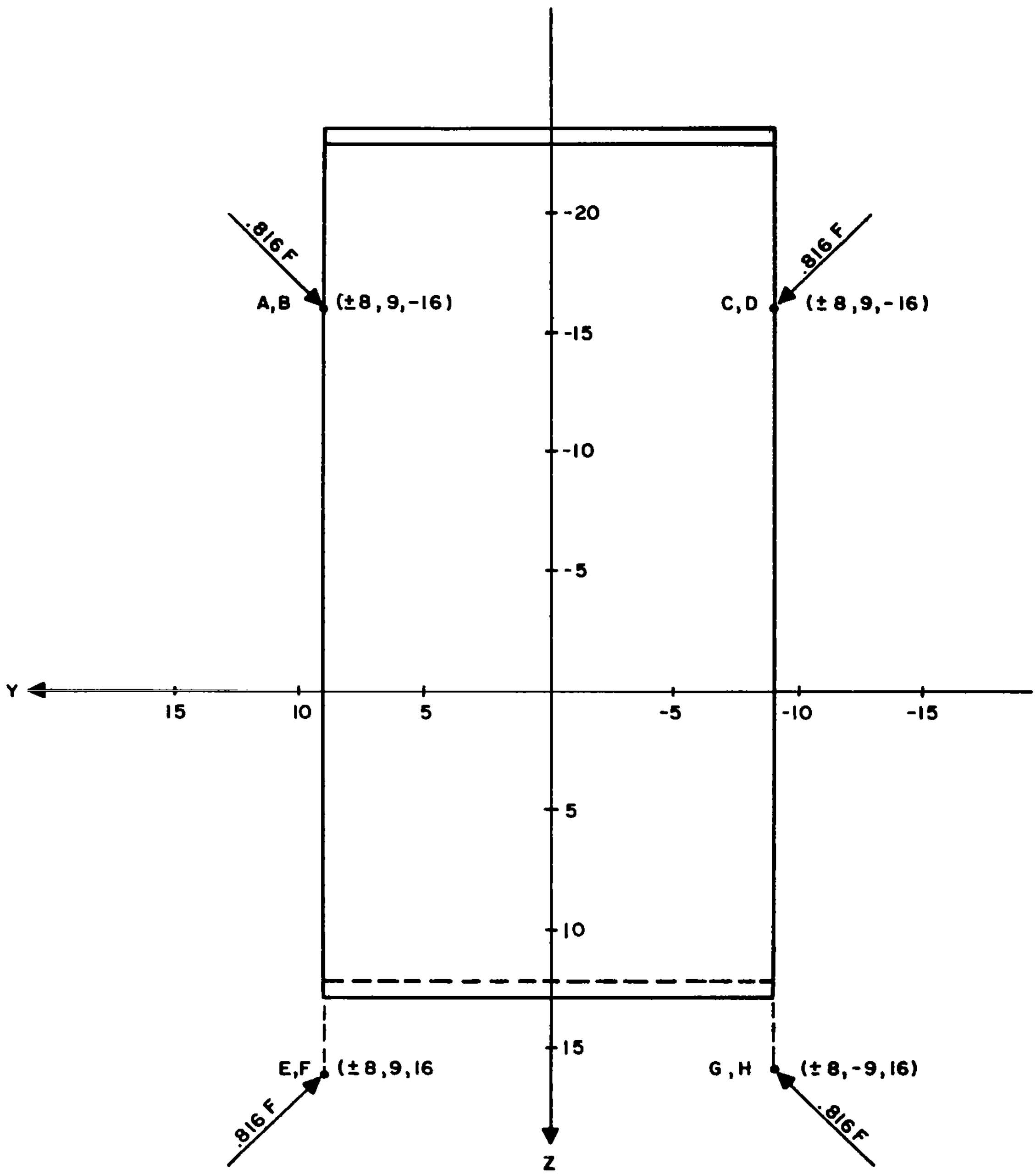
- The torque produced by the jets in the attitude hold mode with no translational thrust should produce an angular acceleration of about 0.4 rad/sec^2 in either direction about the principal axes.

- The torque produced during translational acceleration should be zero for the USAF mean man, suit, and 190-pound backpack in position 1.

- The jets should be located so they can produce restoring torque to control attitude in all three axes for the anticipated shifts in mass center due to the depletion of jet fuel and other supplies.

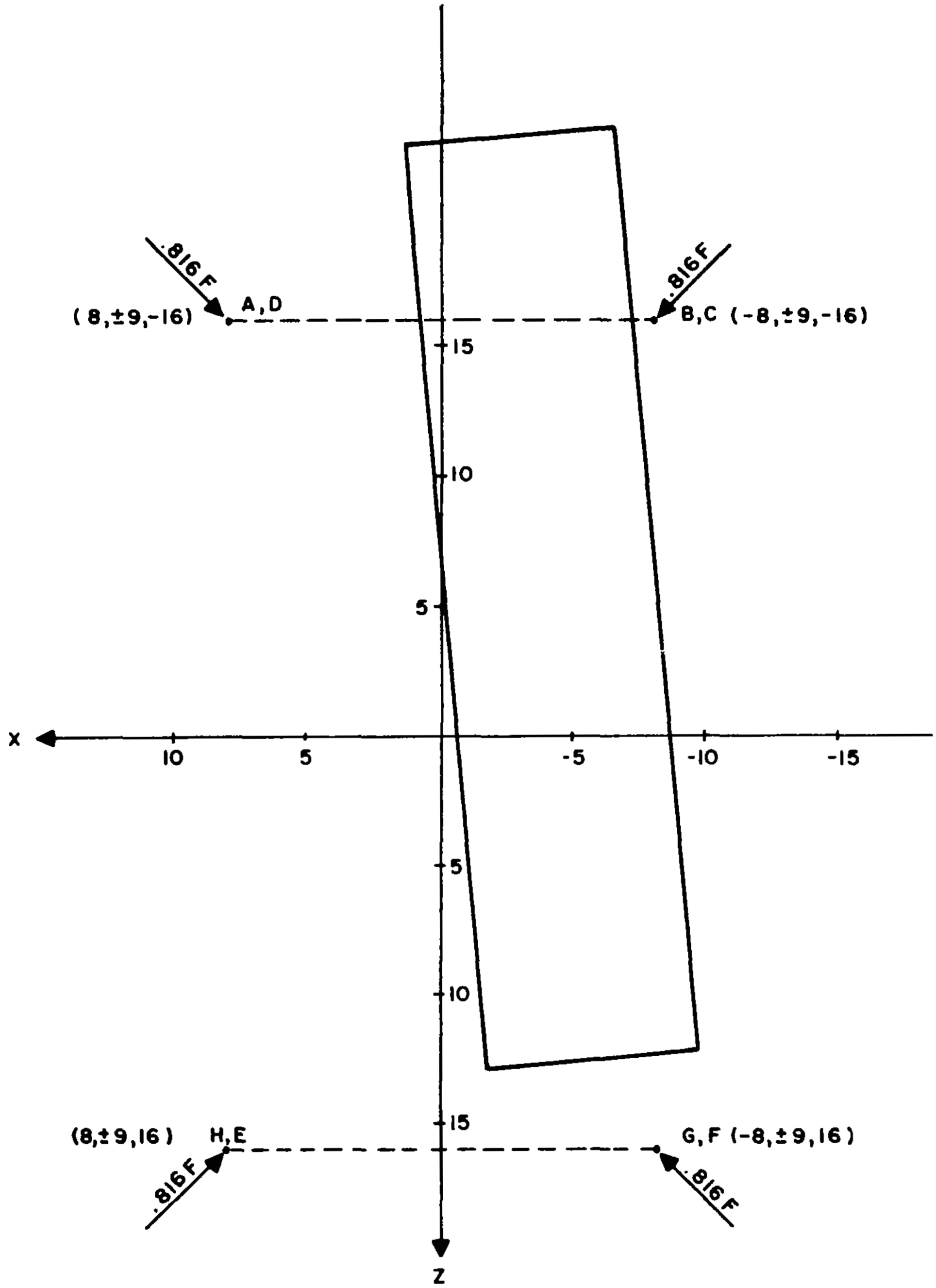
- Jet location should be compatible with the anatomy of the astronaut and construction of the backpack and should minimize the possibility of the jet's impinging on the astronaut's gloves or other regions of the pressure suit.

The translational acceleration of 0.1 g was selected principally as the result of the work of Griffin which indicated that accelerations of 0.1 g produce reasonable maneuverability and fuel consumption.



Note: F = the magnitude of force produced by the jet

Figure 18. Principal Axes for Astronaut Position 1 and 190-lb Backpack (Front View)



Note: F = the magnitude of force produced by the jet

Figure 19. Principal Axes for Astronaut Position 1 and 190-lb Backpack (Side View)

The angular acceleration level of 0.4 rad/sec^2 was selected since it is safe insofar as the astronaut's performance is concerned and provides an acceptable period in the attitude control limit cycle.

It is desirable to reduce torque during translation in order to aid the control of attitude during translations and to simplify the astronaut's task of moving from one location to another. Since the control system turns off the appropriate jets in order to develop restoring torque during translation, the presence of a large perturbing torque will result in a component of translation normal to the desired translation. This, of course, complicates the astronaut's navigation problem.

The jets should not obstruct the astronaut's movements or vision, and they must be located so they can be fastened or appended to the exterior surface of the backpack. This means the jets must be above the astronaut's shoulders (or above a reference line 16 inches in the -Z direction in Figures 18 and 19) and below the reach of hands.

By an iterative design process the locations indicated in Figures 18 and 19 were selected as an acceptable solution.

With the proposed arrangement of the jets, the acceleration capabilities of 15-pound jets are:

Angular Accelerations	
Roll Axis	± 1.01 rad/sec^2
Pitch Axis	± 1.05 rad/sec^2
Yaw Axis	± 0.444 rad/sec^2
During Translation	0.0
Linear Accelerations	
X, Y, and Z Axes	0.092 g

Although the angular accelerations are somewhat higher than desired in the roll and pitch axes, it does not appear possible to reduce these accelerations and meet the requirement of keeping the reaction jets above the astronaut's shoulder. An alternate solution may be to redefine the backpack to "raise" the total mass center toward the shoulders. No significant advantage appears to be gained, however, without a drastic backpack configuration change.

Thrust Logic

Figures 18 and 19 show the location and lines of action of eight thrust jets. These jets will produce the translational and rotational accelerations for rendezvous and attitude control.

It is desirable to apply attitude control torques as couples. The eight-jet configuration can do this in the absence of translational thrust. When translational thrust is applied in the absence of an attitude error, four jets are on. If an attitude error builds up due to misalignment torque during translational thrust, corrective torque can be applied while maintaining some translational thrust by turning two more jets on or by turning two off. The effects, as far as translation and rotation are concerned, are the same. Perhaps an example will suffice to show this. Consider the case where the attitude errors are all zero and upward translational thrust is applied, causing a negative yaw error to develop. Figures 18 and 19 show that upward thrust requires jets E, F, G, and H to fire. Suppose now that misalignment torques cause a negative yaw error. A positive yaw moment could be applied by:

1. Turning off F and H or
2. Turning on A and C or
3. Both turning off F and H and turning on A and C

In Case 1, two jets are left on and the translational thrust is halved. In Case 2, six jets are on and the translational thrust is halved. In Case 3, four jets are on, the restoring torque is doubled and applied as a couple, and the translational thrust is reduced to zero. Case 1 is considered to be the best compromise for both attitude and translational control.

The logic rules for thrust can be summarized as follows:

1. If no translational thrust commands are present, apply couples to correct attitude errors.
2. If a translational thrust command for a given jet is present, that jet shall be on unless an attitude error is present which would be aggravated by the jet remaining on.
3. If such an error is present, the jet is turned off.
4. If an attitude error is present during translational thrust, no jet shall be turned on which opposes the commanded translation.

Next, it is necessary to know the translational and rotational effects produced by each jet. Table 22 summarizes this information.

Table 22. Moments and Forces Produced by Jets

Jet	Moments			Forces		
	Yaw	Pitch	Roll	X	Y	Z
A	+	+	-	-	-	+
B	-	-	-	+	-	+
C	+	-	+	+	+	+
D	-	+	+	-	+	+
E	+	-	+	-	-	-
F	-	+	+	+	-	-
G	+	+	-	+	+	-
H	-	-	-	-	+	-

To describe the function of each jet in words would be a lengthy process, ill suited to electronic design. The notation of Boolean algebra is more compact and more easily translated into circuits.

"1" will represent the transmitting state (in particular, when the variable assigned to a jet is 1, the jet is on). "0" represents the blocking state (jet off). B′, for example, represents the complement of B ("not B").

AB, for example, represents "both A and B". A + B represents "A or B or both".

Definition of variables:

A	Jets	I	- positive yaw error (beyond deadband)
B		J	- negative yaw error (beyond deadband)
C		K	- positive pitch error (beyond deadband)
D		L	- negative pitch error (beyond deadband)
E		M	- positive roll error (beyond deadband)
F		N	- negative roll error (beyond deadband
G			
H			

O - +X (forward) thrust command (from controller)
P - -X (aft) thrust command (from controller)
Q - +Y (right) thrust command (from controller)
R - -Y (left) thrust command (from controller)
S - +Z (down) thrust command (from controller)
T - -Z (up) thrust command (from controller)

$U = I'K'N'$	Auxiliary variables used to denote presence or absence of attitude errors which would be aggravated by a jet remaining on during translational thrust
$V = J'L'N'$	
$W = I'L'M'$	
$X = J'K'M'$	

$Y = J+L+M$	Auxiliary variables used to denote attitude errors which could be corrected by a given jet if certain translational thrust commands are not present
$Z = I+K+M$	
$a = J+K+N$	
$b = I+L+N$	

$$\left.\begin{aligned} d &= P+R+S \\ e &= O+R+S \\ f &= O+Q+S \\ g &= P+Q+S \\ h &= P+R+T \\ j &= O+R+T \\ k &= O+Q+T \\ m &= P+Q+T \end{aligned}\right\}$$

Auxiliary variables used to denote translational thrust commands which call for a given jet in the absence of attitude errors

Referring back to the logic rules, rules 2 and 3 can be abbreviated:

$$\begin{aligned} A &= (P+R+S)\, I'K'N' = dU \\ B &= (O+R+S)\, J'L'N' = eV \\ C &= (O+Q+S)\, I'L'M' = fW \\ D &= (P+Q+S)\, J'K'M' = gX \\ E &= (P+R+T)\, I'L'M' = hW \\ F &= (O+R+T)\, J'K'M' = jX \\ G &= (O+Q+T)\, I'K'N' = kU \\ H &= (P+Q+T)\, J'L'N' = mV \end{aligned}$$

Rules 1 and 4 can be abbreviated:

$$\begin{aligned} A &= (J+L+M)\, O'Q'T' = Yk' \\ B &= (I+K+M)\, P'Q'T' = Zm' \\ C &= (J+K+N)\, P'R'T' = ah' \\ D &= (I+L+N)\, O'R'T' = bj' \\ E &= (J+K+N)\, O'Q'S' = af' \\ F &= (I+L+N)\, P'Q'S' = bg' \\ G &= (J+L+M)\, P'R'S' = Yd' \\ H &= (I+K+M)\, O'R'S' = Ze' \end{aligned}$$

Combining:

$$
\begin{aligned}
A &= dU + Yk' = (P+R+S)\,I'K'N' + (J+L+M)\,O'Q'T' \\
B &= eV + Zm' = (O+R+S)\,J'L'N' + (I+K+M)\,P'Q'T' \\
C &= fW + ah' = (O+Q+S)\,I'L'M' + (J+K+N)\,P'R'T' \\
D &= gX + bj' = (P+Q+S)\,J'K'M' + (I+L+N)\,O'R'T' \\
E &= hW + af' = (P+R+T)\,I'L'M' + (J+K+N)\,O'Q'S' \\
F &= jX + bg' = (O+R+T)\,J'K'M' + (I+L+N)\,P'Q'S' \\
G &= kU + Yd' = (O+Q+T)\,I'K'N' + (J+L+M)\,P'R'S' \\
H &= mV + Ze' = (P+Q+T)\,J'L'N' + (I+K+M)\,O'R'S'
\end{aligned}
$$

Pulse Control

The Orbit Mode System of pulse control uses a series of fixed-width pulses, each actuated when the attitude error exceeds a fixed set point. If the error angle exceeds the set point angle of the last switch, either full thrust can be used or the control system can switch to another mode.

This system is not suited to maintaining small error angles against large disturbance torques since the full thrust condition is reached only at large error angles. Similarly, the Orbit Mode control is not well suited to rate control at large maneuvering rates.

Principal advantage of this system is its propellant economy when no disturbance torque is present. To retain this advantage, a single fixed pulse with a width equal to the minimum repeatable pulse width is used. (In this study, minimum repeatable width was 17 ms.) The set point angle at which this pulse is tripped has been set so that with the largest attitude rate the pulse can control, the set point for the pseudo-rate circuit is not exceeded. Three mr was found to be adequate separation for accelerations as small as 20 mr/sec^2 (ignoring tail-off-effects).

Pseudo Rate Control

The Pseudo Rate Control technique uses a first order lag as a feedback compensation network around an on-off amplifier as shown in Figure 20. Stability of this system under a wide variety of time constants and gains has been demonstrated on an analog computer.

The feedback network in the pseudo rate control system drifts toward null, making the network less accurate as a rate signal source than an exact integrator would be. The "pseudo-integrator" is however, stable, whereas most electronic integrating circuits drift into saturation.

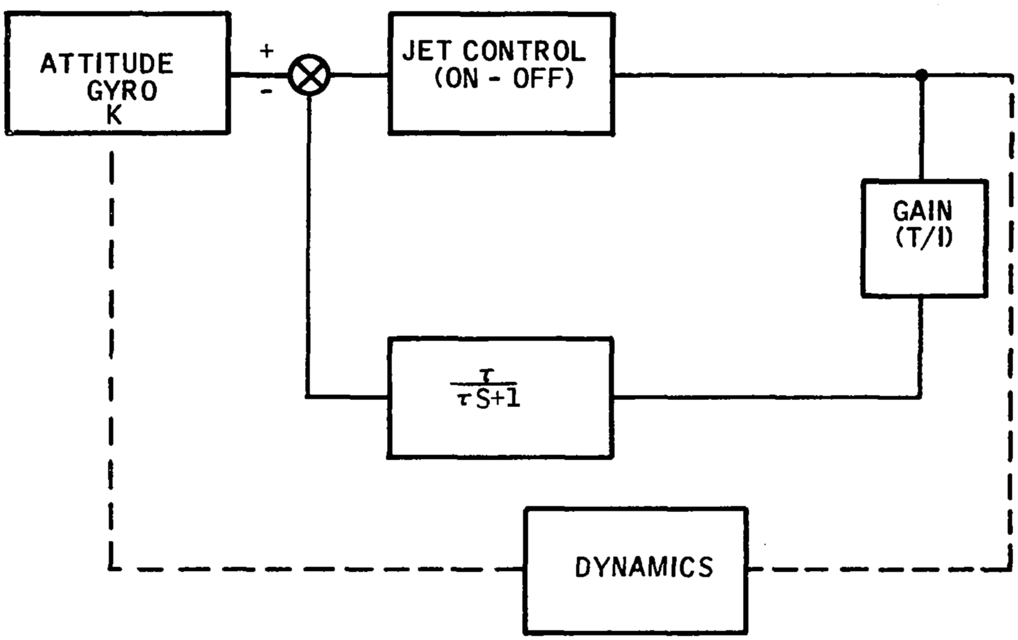


Figure **20.** Pseudo Rate Control Block Diagram

One precaution must be observed when using real solenoid valves in a pseudo-rate control system. Unless the application of the "jet on" voltage to the pseudo-integrator is delayed the same period of time as the "turn on" transport delay of the solenoid valve (5 ms), pseudo-rate voltage could rise fast enough to turn off the jet control amplifier before the solenoid valve opened. If this happens, the jet control amplifier will simply oscillate ineffectually.

Mathematical Models

Reaction Jets -- For simulation purposes, the reaction jet system of paragraph 5.2.3.2 of Section I, Volume II, of this report was used. The mathematical model for a single jet uses a 5 ms turn-on delay, a first-order lag with a time constant of 0.0058 sec for thrust rise, a 1 ms turn-off delay, and first-order lag with a time constant of 0.0058 sec for tail-off. Figure 21 shows time versus thrust traces.

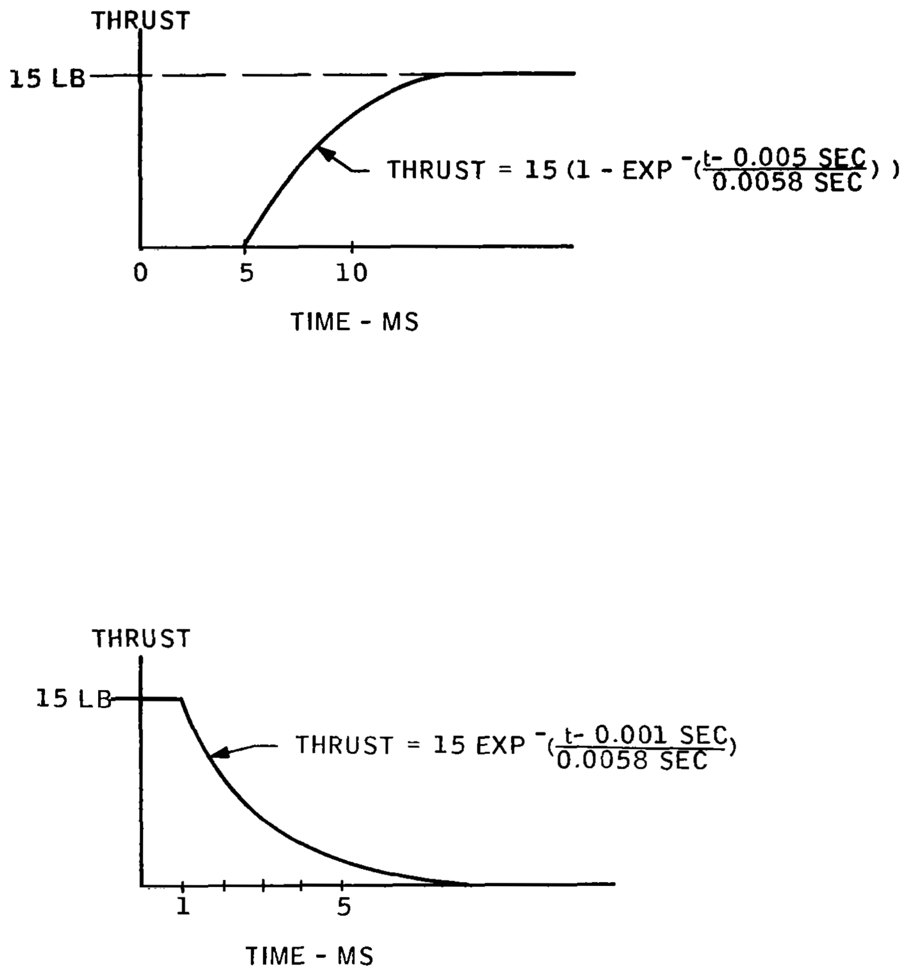


Figure 21. Thrust Rise and Decay Characteristics

Single-Axis Model -- Figure 22 shows a block diagram of the model used to demonstrate stability and select circuit parameters. The pseudo-rate circuit incorporates a 5 ms time delay on the application of thrust-on voltage to the feedback compensation network.

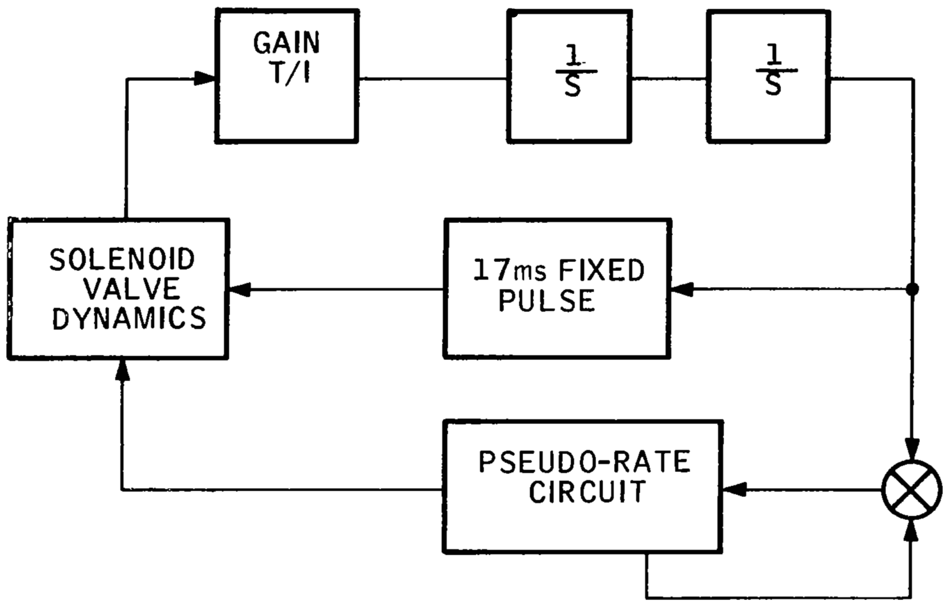


Figure 22. Single-Axis Model Block Diagram

The "flexible" model was developed to study the interaction between control system activity and leg swinging. Although the model nominally describes the pitch axis, it is also suitable for describing the roll axis (with pitch and yaw constrained to zero) if the appropriate values of constants are substituted and the names of the variables changed.

Four degrees of freedom were considered in the analysis -- two translational and one rotational for the upper torso plus AMU, and one rotational for the legs. The legs are considered attached to the upper torso by a frictionless hinge and torsional spring which represents suit and muscular stiffness at the hip joint.

<u>Flexible Man Model</u> -- This is a mathematical model of the pitch axis of the ACS (with roll and yaw constrained to zero) which takes into account the flexibility of the body and pressure suit at the hip joint.

The symbols used are:

F_x	Component of force along the x axis
F_z	Component of force along the z axis
I_1	Moment of inertia of upper torso plus AMU about its center of mass
I_2	Moment of inertia of legs about their center of mass
k	Torsional spring constant of hip joint (including suit)
M	Moment of forces around the y axis
M_1	Mass of upper torso plus AMU
M_2	Mass of legs
R_1	Distance from center of mass of upper torso plus AMU to hip hinge
R_2	Distance from hip hinge to center of mass of legs
x	An axis fixed in the AMU pointing forward
y	An axis fixed in the AMU pointing out the right wing
z	An axis fixed in the AMU pointing from head to toe
X	Inertial coordinate of center of mass of upper torso plus AMU perpendicular to the Z axis
Z	Inertial coordinate of center of mass of upper torso plus AMU from arbitrary origin
θ	Angle between the z and Z axes (the pitch angle)
θ_2	Angle between Z axis and a line drawn through the hip joint and the center of mass of the legs (the pitch angle of the legs)

θ_0 The value of $(\theta_2 - \theta)$ for which the moment due to the torsion spring is zero (see Figure 23.)

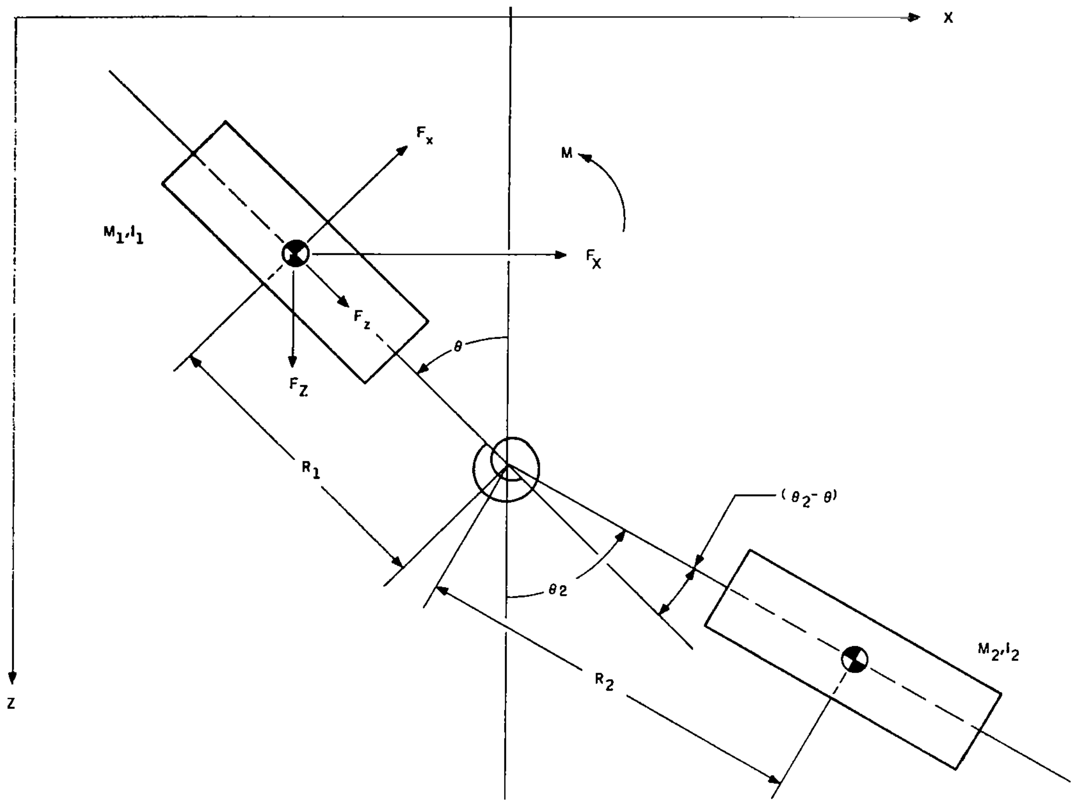


Figure 23. Geometry of "Flexible" Model

The analysis proceeded using the Lagrangian formulation in the form,

$$Qk = \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}k}\right) - \frac{\partial T}{\partial qk}$$

since the forces cannot be derived from a potential.

$$QX = F_x \cos\theta + F_z \sin\theta$$

$$QZ = -F_x \sin\theta + F_z \cos\theta$$

$$Q\theta = M + k(\theta_2 - \theta - \theta_o)$$

$$Q\theta_2 = -k(\theta_2 - \theta - \theta_o)$$

The resulting equations of motion are:

$$\begin{aligned} &-F_x \cos\theta - F_z \sin\theta + (M_1 + M_2)\ddot{X} + M_2 R_1 \cos\theta\,\ddot{\theta} \\ &- M_2 R_1 \sin\theta\,\dot{\theta}^2 + M_2 R_2 \cos\theta_2\,\ddot{\theta}_2 - M_2 R_2 \sin\theta_2\,\dot{\theta}_2^{\,2} = 0 \end{aligned} \qquad \text{(V-1)}$$

$$\begin{aligned} &F_x \sin\theta - F_z \cos\theta + (M_1 + M_2)\ddot{Z} - M_2 R_1 \sin\theta\,\ddot{\theta} \\ &- M_2 R_1 \cos\theta\,\dot{\theta}^2 - M_2 R_2 \sin\theta_2\,\ddot{\theta}_2 - M_2 R_2 \cos\theta_2\,\dot{\theta}_2^{\,2} = 0 \end{aligned} \qquad \text{(V-2)}$$

$$\begin{aligned} &-M - k(\theta_2 - \theta - \theta_o) + (I_1 + M_2 R_1^2)\ddot{\theta} + M_2 R_1 \cos\theta\,\ddot{X} \\ &- M_2 R_1 \sin\theta\,\ddot{Z} + M_2 R_1 R_2 [\ddot{\theta}_2 \cos(\theta_2 - \theta) - \dot{\theta}_2^{\,2} \sin(\theta_2 - \theta)] = 0 \end{aligned} \qquad \text{(V-3)}$$

and

$$\begin{aligned} &k(\theta_2 - \theta - \theta_o) + (I_2 + M_2 R_2^2)\ddot{\theta}_2 + M_2 R_2 \cos\theta_2\,\ddot{X} \\ &- M_2 R_2 \sin\theta_2\,\ddot{Z} + M_2 R_1 R_2 [\ddot{\theta} \cos(\theta_2 - \theta) + \dot{\theta}^2 \sin(\theta_2 - \theta)] = 0 \end{aligned} \qquad \text{(V-4)}$$

Three-Axis "Rigid" Model-- The three axis "rigid" model was developed to study the complete ACS problem. It was felt that the presence of flexibility might make it difficult to assess the effect of a given control system parameter. This model includes all coupling between body rates and can deal with arbitrary changes in the inertia tensor. The symbols used are:

p, q, r	Angular rates about the body x, y, and z axes
T_x, T_y, T_z	Torques about the body x, y, and z axes
I_{xx}, I_{yy}, I_{zz}	Moments of inertia about the body x, y, and z axes
I_{xy}, I_{yz}, I_{zx}	Products of inertia

The equations of motion are:

$$
\begin{aligned}
T_x &= I_{xx}\dot{p} - qr(I_{yy} - I_{zz}) - I_{xy}(\dot{q} - rp) - I_{yz}(q^2 - r^2) - I_{zx}(\dot{r} + pq) \\
T_y &= I_{yy}\dot{q} - rp(I_{zz} - I_{xx}) - I_{xy}(\dot{p} + qr) - I_{yz}(\dot{r} - pq) - I_{zx}(r^2 - p^2) \\
T_z &= I_{zz}\dot{r} - pq(I_{xx} - I_{yy}) - I_{xy}(p^2 - q^2) - I_{yz}(\dot{q} + rp) - I_{zx}(\dot{p} - qr)
\end{aligned}
\tag{V-5}
$$

For ease of analog simulation, equations (V-5) are used with the axes coincident with the principal axes.

The equations then reduce to:

$$
\begin{aligned}
T_x &= I_{xx}\dot{p} - qr(I_{yy} - I_{zz}) \\
T_y &= I_{yy}\dot{q} - rp(I_{zz} - I_{xx}) \\
T_z &= I_{zz}\dot{r} - pq(I_{xx} - I_{yy})
\end{aligned}
\tag{V-6}
$$

From these are derived the expressions for the Euler rates in terms of body rates:

$$\dot{\psi} = \frac{q \sin \phi}{\cos \theta} + \frac{r \cos \phi}{\cos \theta}$$

$$\dot{\theta} = q \cos \phi - r \sin \phi \qquad \text{(V-7)}$$

$$\dot{\phi} = p + q \tan \theta \sin \phi + r \tan \theta \cos \phi$$

Equations (V-6) can be solved for $\dot{p}$, $\dot{q}$, and $\dot{r}$, which can then be integrated to find p, q, and r. Equations (V-7) can then be used to find $\dot{\psi}$, $\dot{\theta}$, and $\dot{\phi}$, which, in turn, can be integrated to find ψ, θ, and ϕ.

Since a successful ACS will restrict all of the angles to small quantities, it is possible to simplify Equations (V-7) to:

$$\dot{\psi} = r, \quad \dot{\theta} = q, \quad \dot{\phi} = p$$

ACS SIMULATIONS

The main effects which were to be studied by means of analog simulations were:

- Variations of switching points
- Variations of pseudo rate gain and time constant
- Behavior during translational acceleration
- Interaction between the control system and hip joint flexibility
- Performance of the system when inertial coupling is included and control activity is present in all three axes

The following sections discuss the three simulations used to explore these questions -- a single-axis "rigid" simulation, a single-axis "flexible" simulation and a three-axis "rigid" simulation.

Single-Axis Rigid Simulation

A single-axis rigid-body simulation was run to determine stability and gross performance. The configuration simulated was Position 1, 190-lb backpack. Figure 24 represents a single-axis block diagram of the ACS. The principal components of the system are the attitude gyro, the switching logic, the electronics for driving the reaction jet valves, the valves and reaction jets, and a first-order lag network. The lag network provides a "pseudo rate" for damping. In operation, the gyro provides a signal proportional to the astronaut's departure from the selected attitude. This signal goes to the switching logic which has a deadband of 12 milliradians. Therefore, when the gyro output is less than 12 milliradians, the control system takes no action. When the gyro output indicates an attitude error of ±12 milliradians, the switching logic provides a fixed-width pulse of 17 milliseconds to the valve drivers. The deadband was selected as ±12 milliradians so as to be responsive to the requirement of holding attitude to ±1 degree when no translational thrust is applied. The 17-millisecond pulse width was selected as the minimum effective pulse width normally obtainable.

If the fixed pulse is insufficient to null or reverse the attitude rate and the attitude error continues to increase, the pseudo rate circuit turns on the jets when the attitude reaches ±17 milliradians. This switching point is placed as close as possible to the fixed-pulse switching point without activating both the fixed pulse and pseudo rate control unnecessarily. The ±17 milliradian switch point was selected after some experimentation on the analog computer. The signal used to turn the jet valves on is also used to generate the pseudo rate. The signal is lagged with a time constant of T seconds, and the resulting signal is added to the attitude error with a relative gain of K. The sum of these two signals then drives the switching logic. As a result the pulse width in the pseudo rate mode varies as a function of the vehicle attitude rate and thus has a damping effect on system operation.

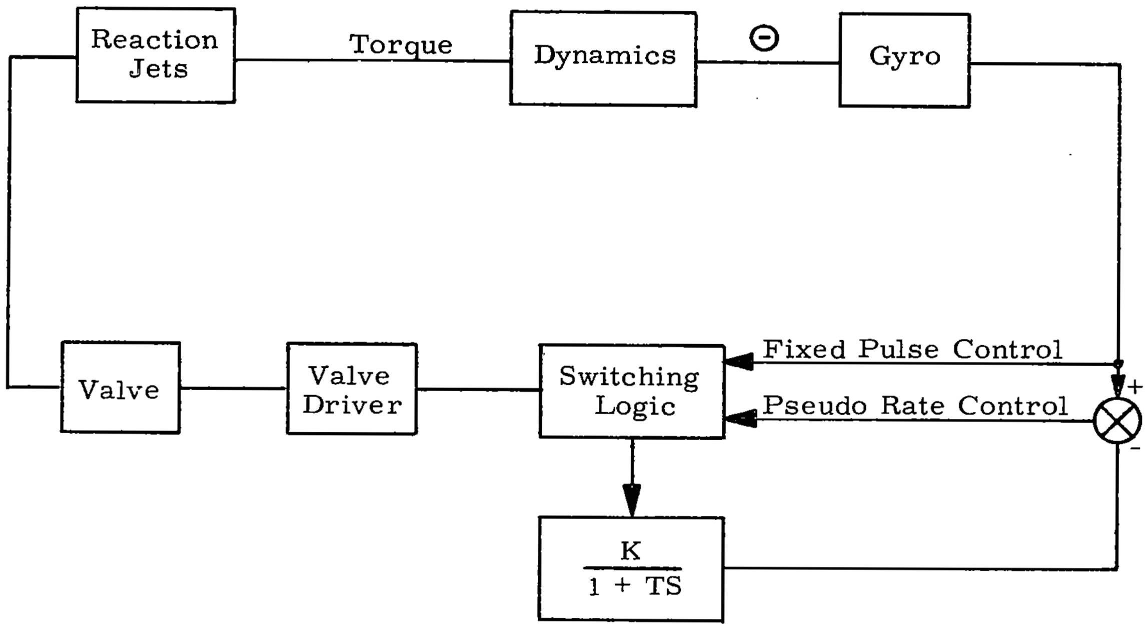


Figure 24. Block Diagram of Selected Control System

The diagram of this simulation is shown in Figure 25. In addition to the control system and astronaut, the dynamics of the reaction jets and associated valves were included. The results of the simulation study are summarized in Figure 26 and Table 23. Figure 26 is a collection of phase-plane plots recorded from the simulations. The initial conditions for all the plots are the same in order to have a basis of comparison of the performance with different time constants and gains in the pseudo rate lag network. The initial conditions were zero attitude and 160 milliradians per second attitude rate. Table 23 indicates the relative fuel consumption of the system for the various combinations of gain and time constant presented in Figure 26. Four values of gain and four values of time constants were investigated. The time constants were 1, 3, 5, and 8 seconds; and the gain relative to the attitude gain was 1, 3, 5, and 8. On the basis of these results, a lag network with a time constant of 5 seconds and a gain of 5 will be adequate; however, it does not appear that the system performance is too sensitive to these parameters, and considerable latitude can be exercised in their selection.

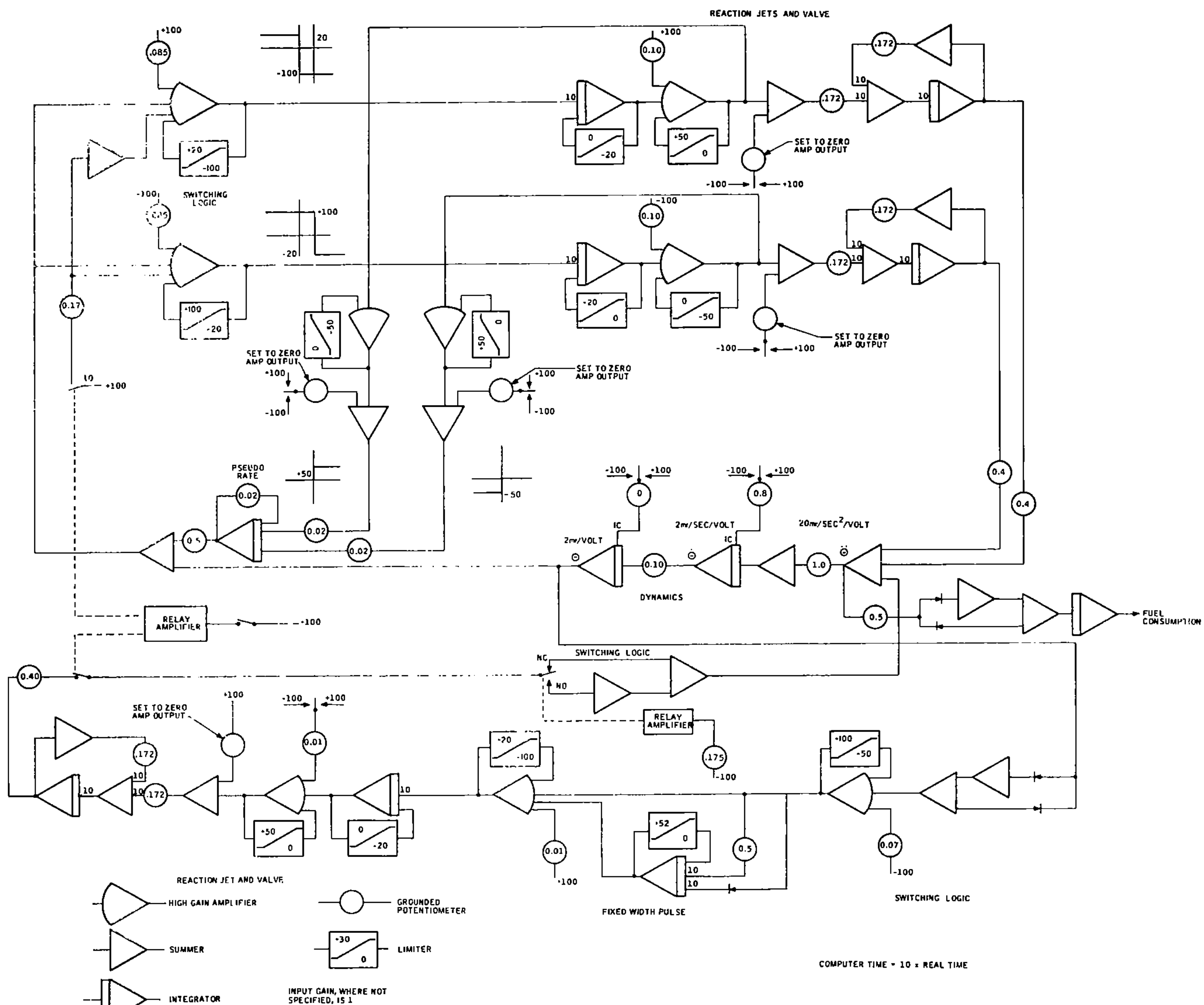


Figure 25. Single-Axis Rigid Body Simulation of ACS

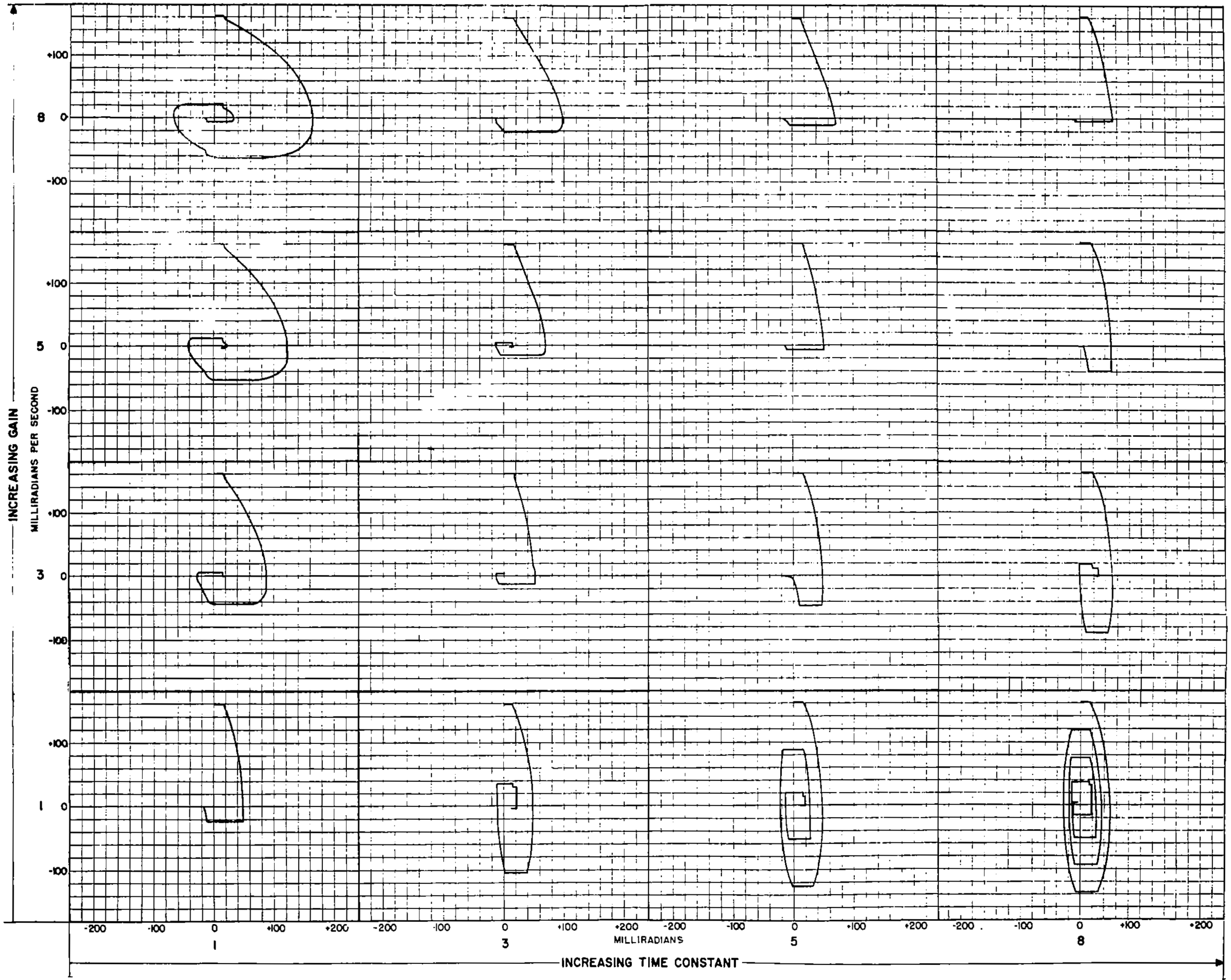


Figure 26. System Performance With Pseudo Rate

Table 23. Relative Fuel Consumption for Various Parameter Values in Pseudo Rate Circuit

Pseudo Rate Control	Relative Fuel Consumption			
Gain \ Time Constant	1	3	5	8
1	12.9	30.3	53.6	100
3	12.5	10.9	16.7	25.9
5	12.6	10.2	10.5	15.6
8	12.7	9.6	9.8	10.2

When the attitude rates are less than 3.35 milliradians per second, the system will limit cycle within the deadband of the fixed pulse. When the limit cycle is symmetrical, the period is 36 seconds and the amplitude is 15 milliradians.

Flexible Man Simulation

The mathematical model of a man flexible at the hip joint was programmed on an analog computer. The configuration simulated was Position 1, 190-lb back-pack. An undamped linear torsion spring at the hip joint was assumed. Any control activity induced a persistent oscillation which masked the effects under investigation. It was felt that these oscillations did not realistically simulate the motion of a man in a pressure suit.

Since the angular velocities of the upper body and legs were available in the existing simulation, a moment proportional to their difference was used to oppose the motion. The gain of the difference signal was adjusted so that an initial difference in the attitudes of the upper body and legs was damped with one overshoot.

The effects of varying pseudo rate time constant and gain were studied using the simulation with damping. The results showed that the system was extremely tolerant to time constant and gain variation in the absence of translational or rate commands.

The response of the system to translational acceleration was also studied. When maximum misalignment torque was applied, starting with initial conditions of zero in attitude, attitude rate, and pseudo rate, no combination of pseudo rate time constant or gain could control the attitude within the limits of $\pm 5^\circ$ (87 mr) established in Section I, **Appendix A** of this report. The apparent reason for this was that the control could not be actuated until the attitude error exceeded 17 mr. By this time the attitude rate was so large that the control could not reverse it before the attitude error had exceeded 87 mr.

For comparison, a control system using rate feedback was investigated. With a gain of 0.5 and 1.0, this system controlled the attitude error to within 20 mr during translational acceleration with maximum misalignment torque. This system also followed input command rates very smoothly and accurately.

An initial rate of 400 mr/sec was placed into the simulation, and various pseudo rate and rate feedback control systems were studied. All of them damped the initial rate and started the attitude error toward zero. This included rate feedback systems with gains from 0.1 to 1, and pseudo rate systems with time constants ranging from 1 to 8 seconds and gains ranging from 0.1 to 1.0.

Results of the "flexible man" study point out the desirability of having a rigid structure (or astronaut) for control purposes. Further study is required to define the best approach to the problem (that is, whether rate gyros should be included or whether the astronaut should be "rigidized"). In order not to affect progress under the contract, no change was made to the control system as defined. Rate gyros can be easily added and accommodated in the circuitry if a need is definitely established in further development.

Figure 27 shows the analog computer traces of a typical pseudo rate system with 0.1 g translational acceleration. Figure 28 shows the behavior of a rate feedback with 0.1 g translational acceleration, with gains of 0.1, 0.5 and 1.0.

Three-Axis Rigid Simulation

A three-axis rigid simulation was programmed on an analog computer to demonstrate the performance of the system and to make the final choice of switching points and pseudo-rate parameters.

Figures 29, 30, and 31 show the responses of nine systems to initial rates of 100 mr/sec in all three axes. The configuration simulated is Position 1-190 lb back pack. The maximum overshoot in roll (picked as a typical response) is shown in Table 24.

Table 24. Maximum Overshoot in Roll with Initial Rates of 100 mr/sec in All Axes

		Pseudo Rate Time Constant (sec.)		
		1	5	8
	1	17 mr	30 mr*	30 mr*
Gain	5	36 mr	36 mr	31 mr
	8	47 mr	44 mr	36 mr

*Oscillatory response

These systems used the switching points developed in the single-axis simulation - ±12 mr for the 17 ms pulse and ±17 mr for the pseudo rate circuit. The system judged to be best had a gain of 1 and a pseudo rate time constant of 1 sec.

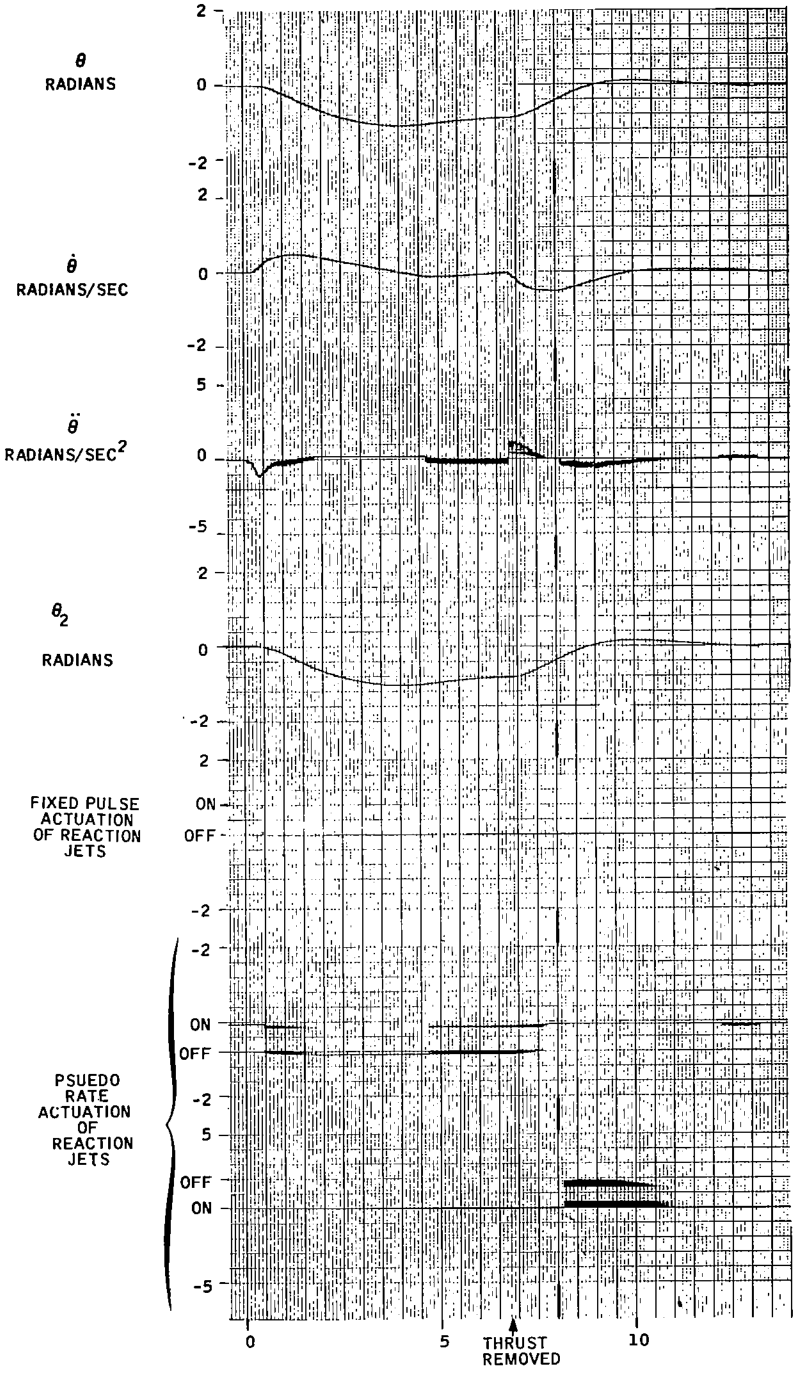


Figure 27. System Response to 0.1 g Thrust in +X Direction, Pseudo-Rate Time Constant = 1 Sec, Pseudo-Rate Gain = 0.5 Sec

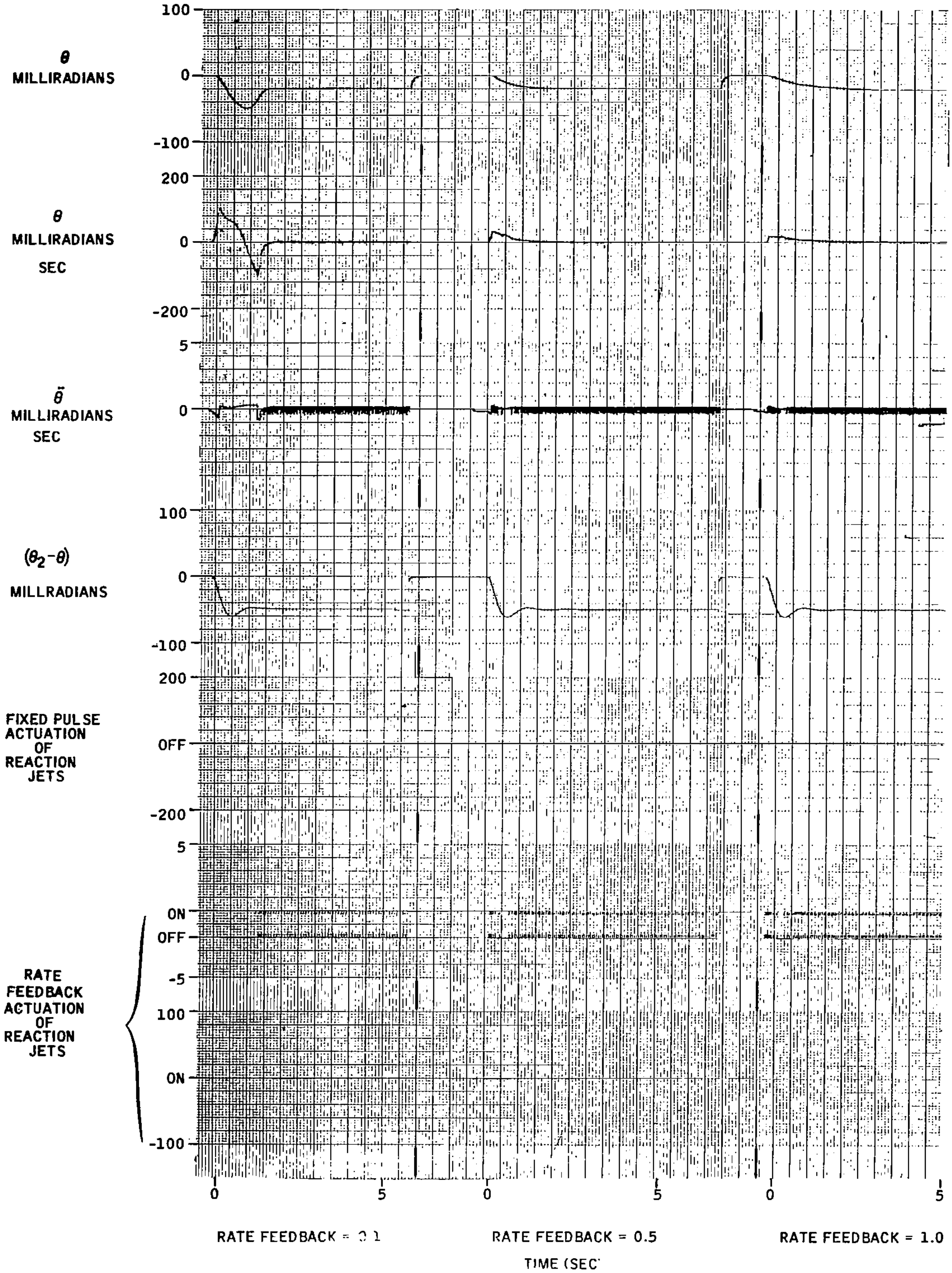


Figure 28. System Response to a Steady 0.1 g Thrust in +X Direction

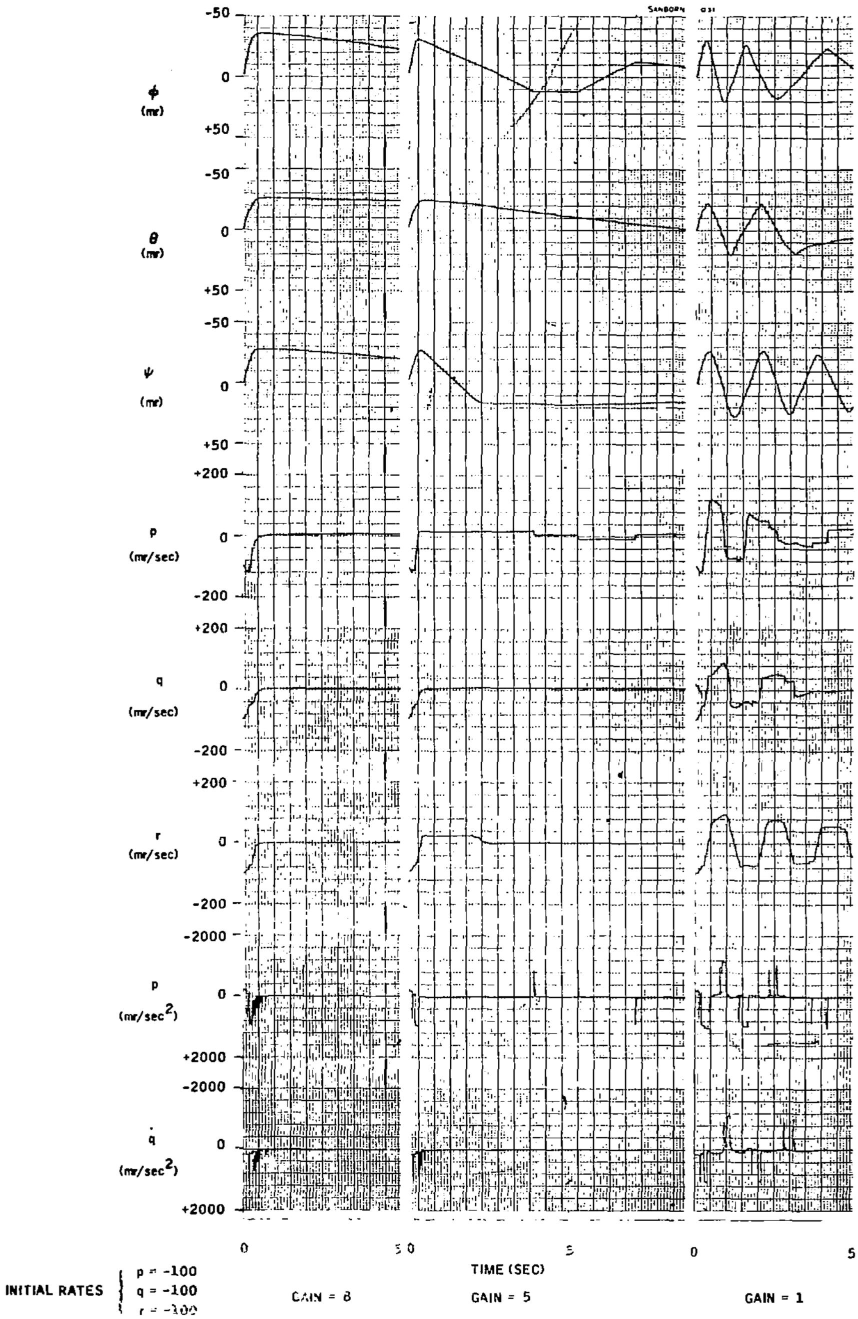


Figure 29. Pseudo-Rate F/B Time Constant = 8 Sec, Position 1, 190-lb Backpack

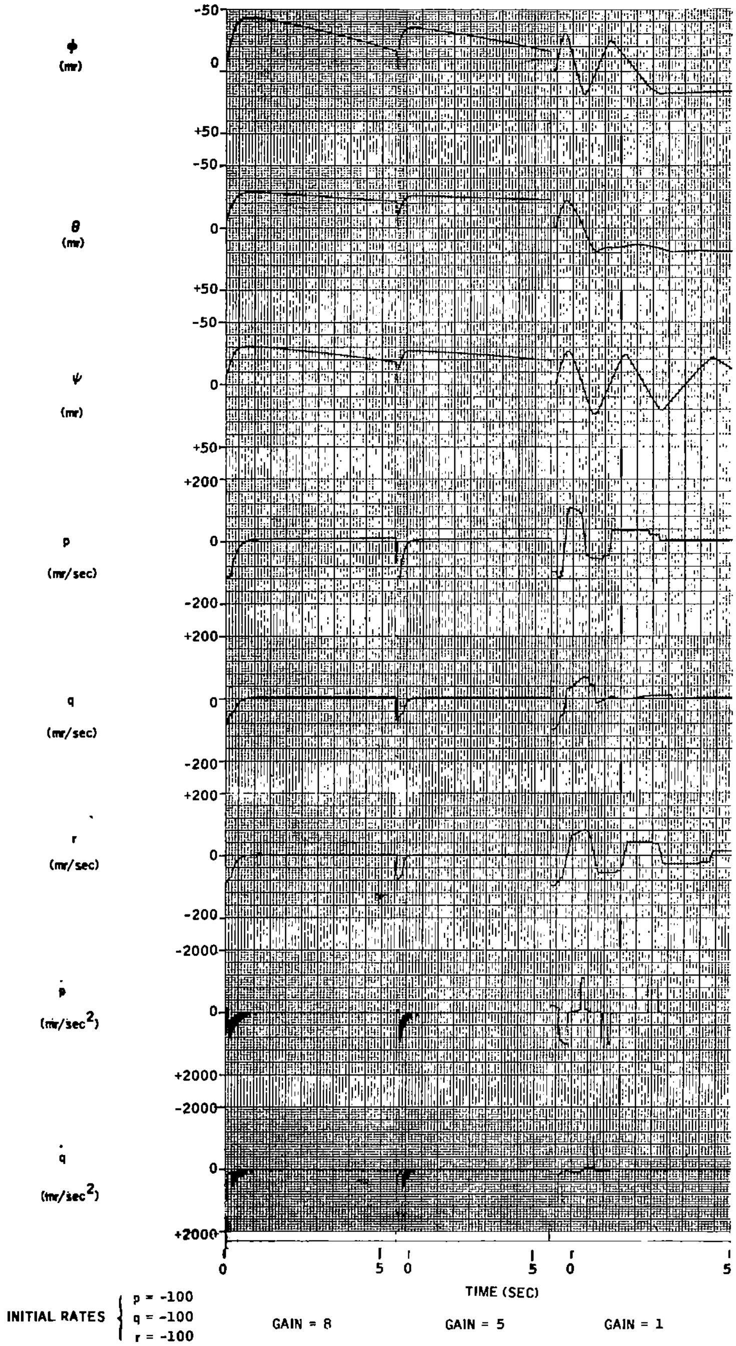


Figure 30. Pseudo-Rate Time Constant = 5 Sec, Position 1, 190-lb Backpack

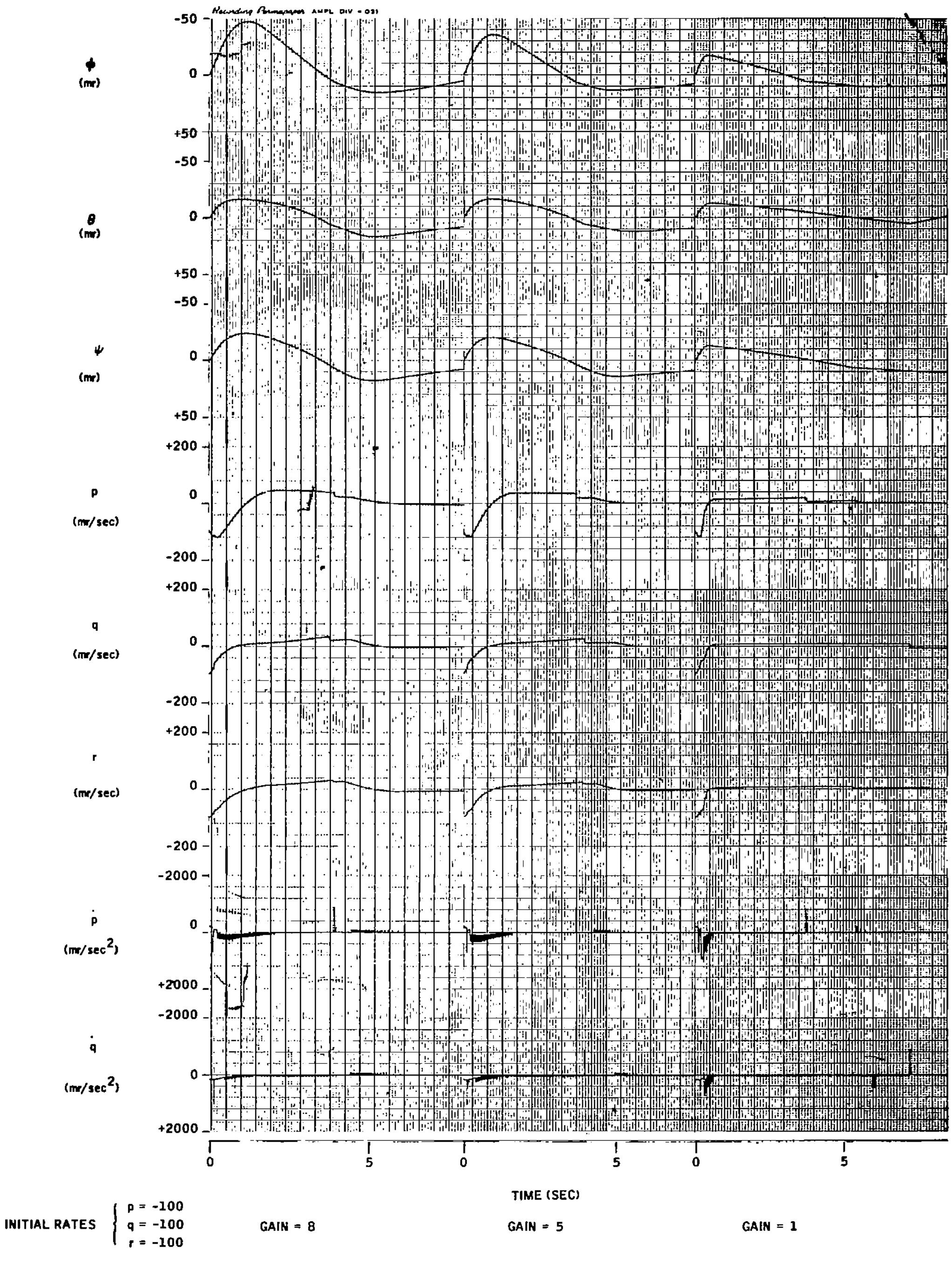


Figure 31. Pseudo Rate F/B Time Constant = 1 Sec, Position 1, 190-lb Backpack

Limit cycle behavior was demonstrated by inserting small initial rates. Figure 32 shows the system controls attitude within the 1° (17.5 mr) requirement.

Figure 33 shows the response of the system to command input rates of 20 deg/sec (350 mr/sec). The subscript, ϵ, is used to denote the error angles measured by the gyros being torqued. The behavior in roll and pitch is smooth and the rate settles out to the command rate after one overshoot. In yaw, however, the response is less well damped, due to the lower level of angular acceleration.

Figure 34 shows a time history of yaw attitude, ψ, measured in this case from the yaw attitude existing at the time the command was inserted. ψ_c is the angle required to maintain the command rate. The error angle is the difference between ψ and ψ_c. The system converges to a small attitude offset in four overshoots.

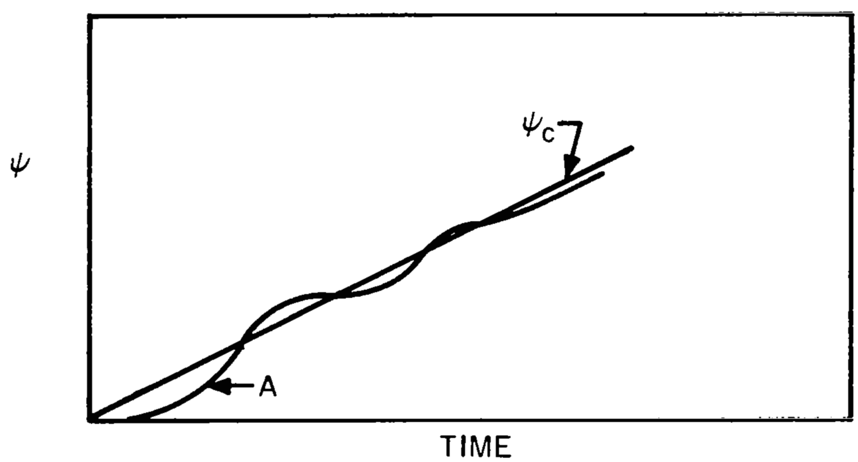


Figure 34. Time History of Yaw Attitude

The peak rates in all cases are below the 40 deg/sec requirement.

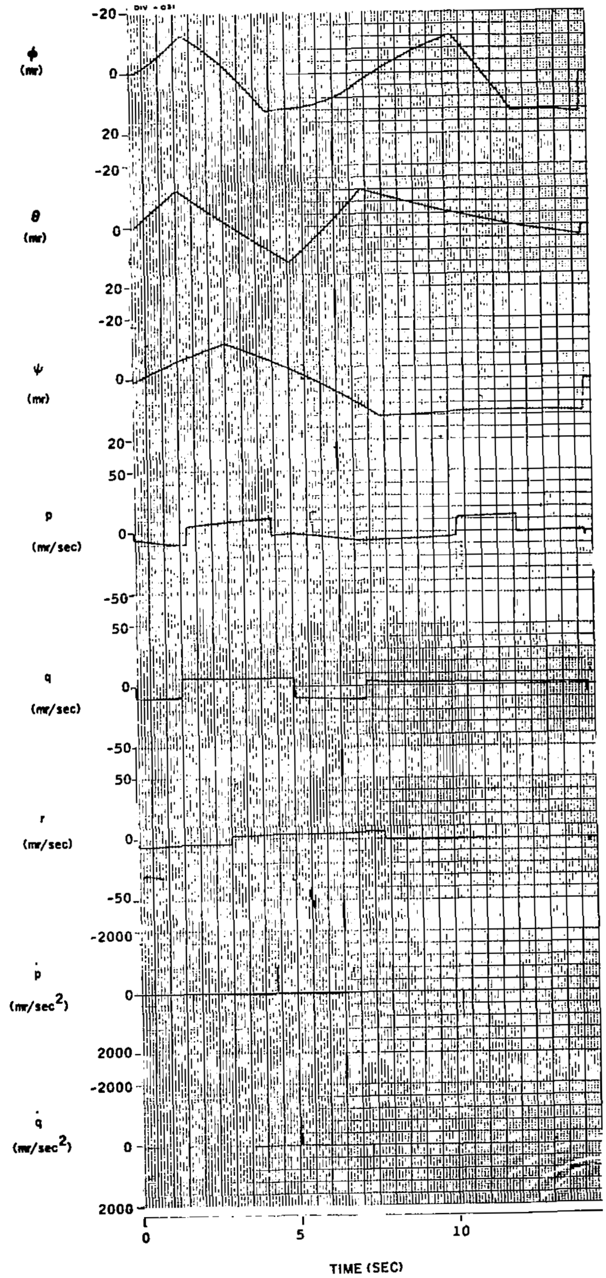


Figure 32. Limit Cycle Behavior, Position 1, 190-lb Backpack

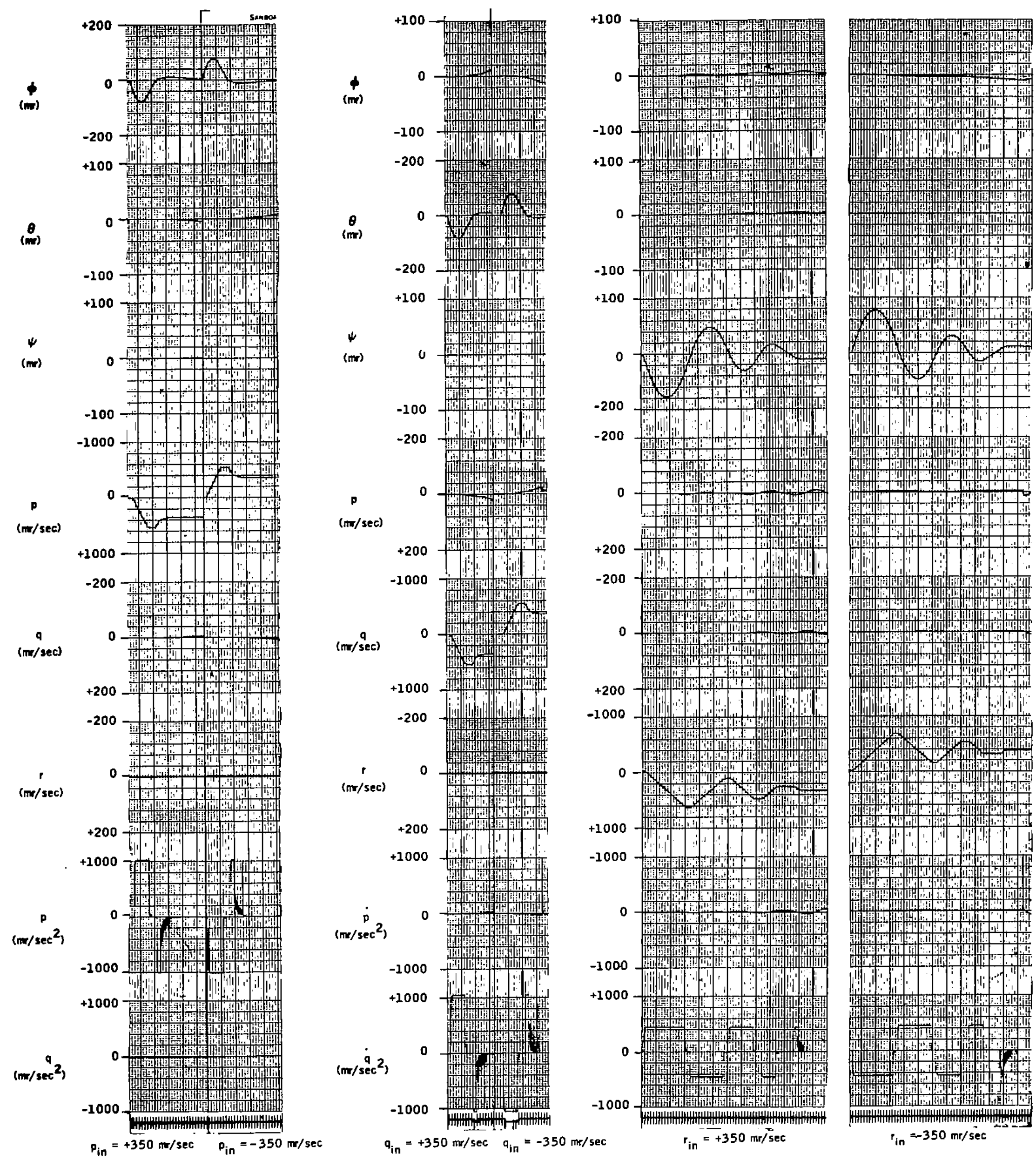


Figure 33. 20 Deg/Sec Command Input Rate, Position 1, 190-lb Backpack

Figure 35 shows the response of the system to command input rates of 3 deg/ sec. (52.5 mr/sec). The response is smooth and well damped in all axes. The precision rate of .15 deg/sec was programmed but the effects to be shown were masked by integrator drift.

All of the simulations have so far been for the astronaut in position one with a 190-lb backpack. The jets are aimed so as to produce no misalignment torque in this configuration to simulate the behavior of the system during translational acceleration, with misalignment and cm shift due to postural variation and backpack depletion. The astronaut was programmed in position four (arms level with shoulders) and a 120-lb backpack. (It should be noted extreme postural variations e.g. position five, can move the cm so that the system becomes unstable during translational acceleration and hence should be avoided at these times.) The behavior during +X and -X translational acceleration is shown in Figure 36. The largest attitude excursion is in pitch, 1.8 degrees, (32 mr). The requirement is that the system hold attitudes within 5 degrees, (87 mr).

Figure 37 shows the limit cycle behavior of the system. Small initial rates were used to induce limit cycling. All attitude excursions are less than one degree (17.5 mr). It was suspected that the eight jet configuration possessed some redundancy.

The behavior of the system was studied with jet A disabled. The configuration simulated was Position 1-190 lb backpack. The system arrested an initial rate of 100 mr/sec in each of the three axes. Figure 38 shows the behavior of the system during -X translational acceleration.

This direction of acceleration was chosen because jet A is used under normal conditions and because the effects of misalignment would be most severe. Note that the worst attitude excursion is less than 80 mr (4.6 deg).

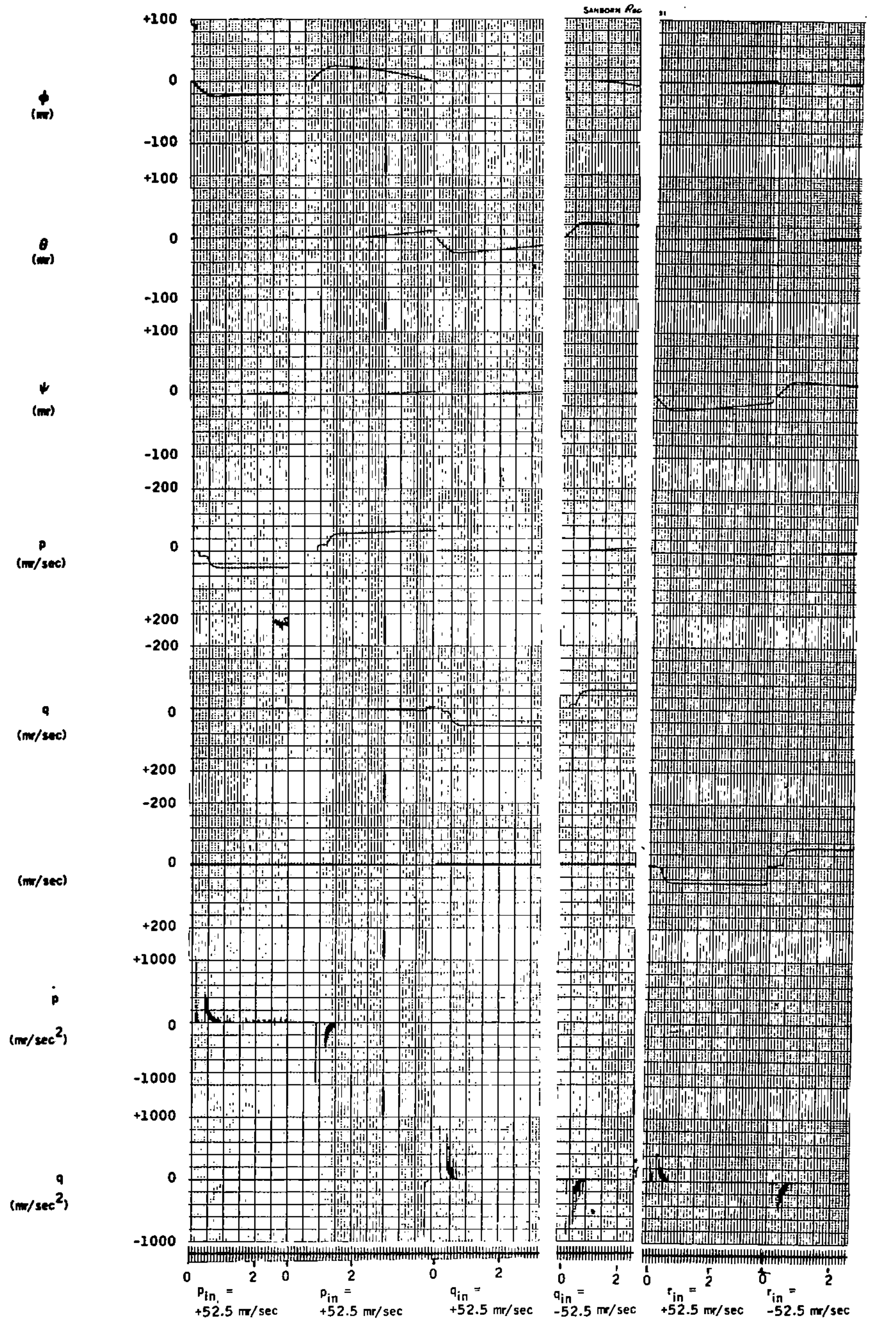


Figure 35. 3 Deg/Sec Command Input Rate, Position 1, 190-lb Backpack

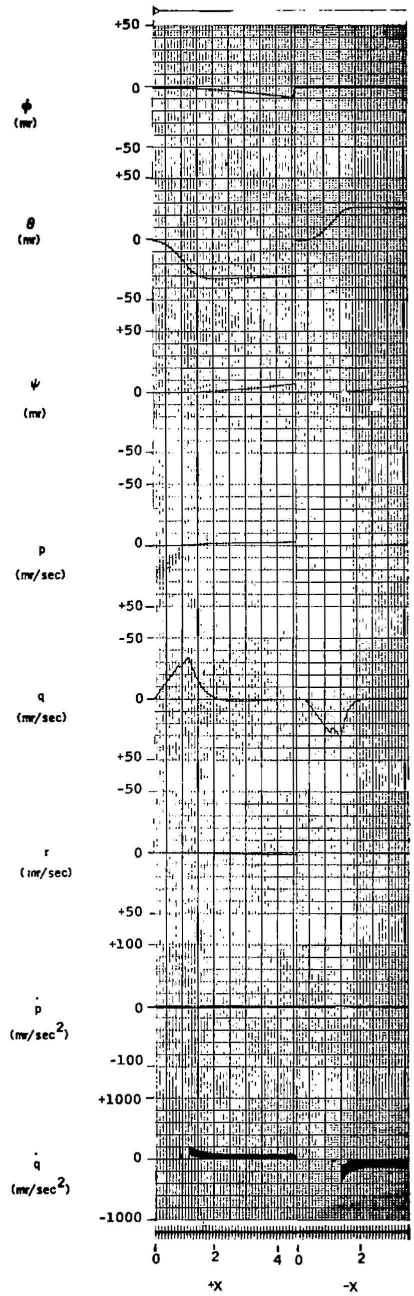


Figure 36. Behavior During Translational Acceleration, Position 4, 120-lb Backpack

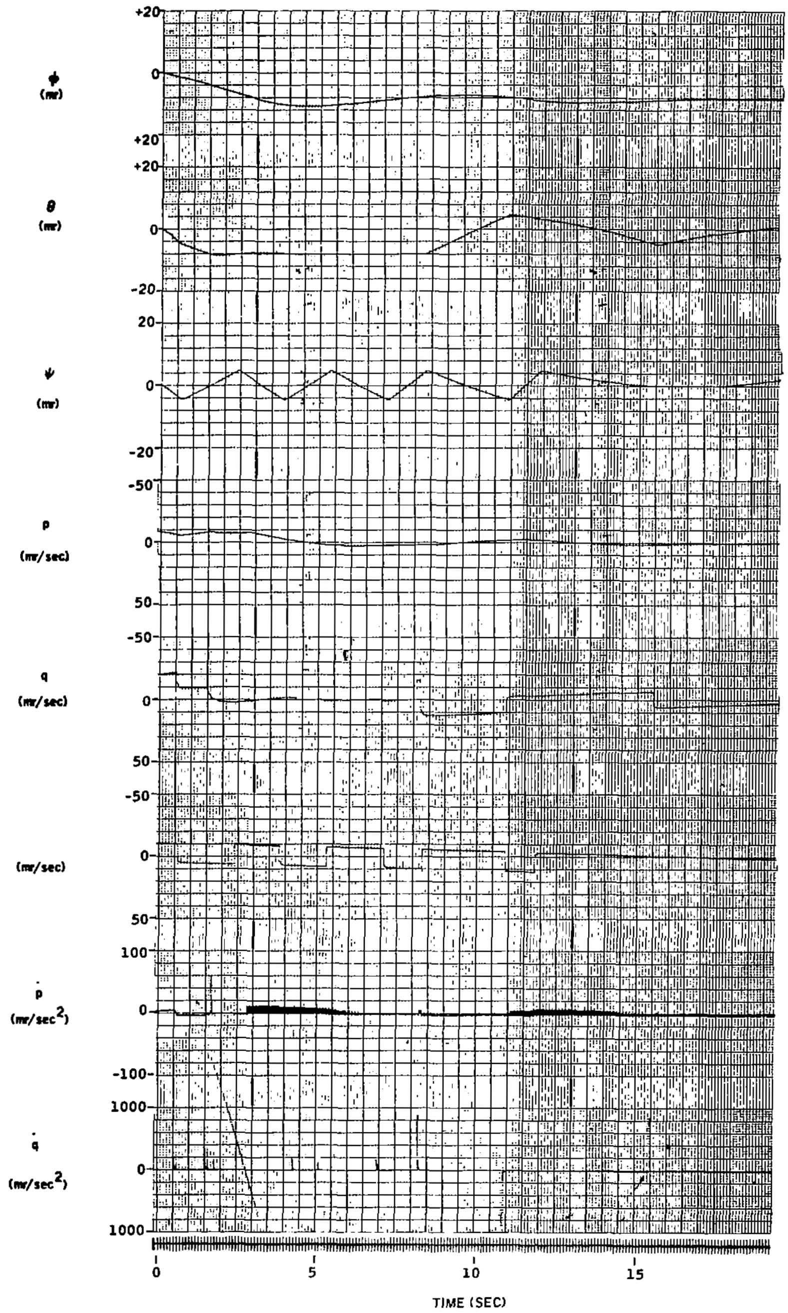


Figure 37. Limit Cycle Behavior, Position 4, 120-lb Backpack

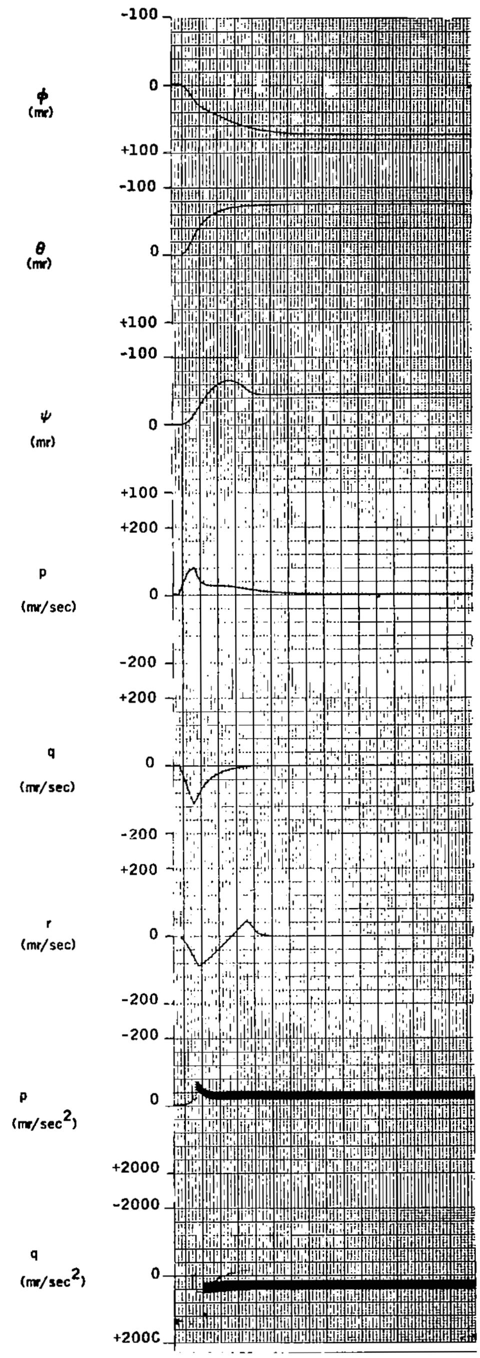


Figure 38. Behavior During -X Translational Acceleration With Jet "A" Disabled, Position 1, 190-lb Backpack

Summary of Results

An attitude control system with the following characteristics will meet the requirements:

- a fixed 17 ms pulse at ±12 mr
- a pseudo rate feedback with a gain of 1 and time constant of 1 sec, with deadband limits of ±17 mr

A block diagram of a typical control axis is shown in Figure 39.

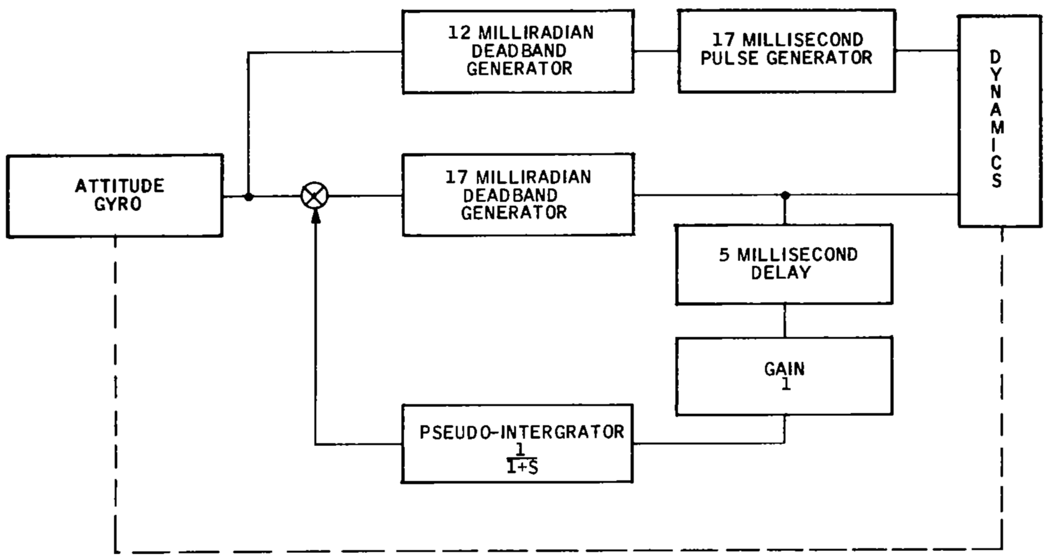


Figure 39. Typical Control Axis Block Diagram

A potential source of control system trouble lies in the effects of pressure suit flexibility. It may be necessary to "rigidize" the suit or include rate gyros in the control system. It was not felt that the pressure suit configuration was sufficiently well defined to warrant inclusion of rate gyros.

The eight jet configuration is stable and is capable of producing translational acceleration with one jet disabled.

Excessive postural variations can cause the system to be unstable during translational accelerations. It is felt that these are under the astronaut's control, and therefore do not constitute a serious problem. "Rigidizing" the suit would, of course, prevent any such variations.

CIRCUIT DESIGN

The prime considerations in the AMU - ACS circuit design were performance, size, weight, power, reliability and economy. These considerations prompted the selection of microminiature electronics. An industry survey of the state of the art in microminiature electronics was made emphasizing proven performance and availability. This company began work in the integrated electronics field at an early date. Its method of fabricating complete circuits on monolithic silicon substrates by planar diffusion has brought the company to prominence among integrated circuit manufacturers.

The analog circuitry of the ACS requires good stability and noise rejection as well as economical use of the available signal levels. Differential amplifiers are used in this system mechanization because their stability and noise rejection characteristics are better than ordinary single-ended amplifiers. Properly used, differential amplifiers have a greater versatility than single-ended amplifiers. Double-ended axis computer bridges were selected for use because they eliminate the need for inverting amplifiers.

The combination of the double-ended bridge with the differential amplifier assists the designer's ingenuity in reducing the parts count.

To simplify discussion, the ACS circuitry is divided into the following functional units. All Honeywell SK drawings are contained in **Appendix B** of this report.

1. Command Logic SK92529
2. Temperature Control Amplifier SK92529
3. Jet Driver SK92530
4. Sensor Torquer Amplifier SK92531, 2, 3
5. Axis Computer SK92531, 2, 3
6. Power Supply SK92534

Command Logic - SK92529

The control logic was expressed in Boolean equations factored to their greatest simplicity. These equations were mechanized using NAND/NOR logic so as to yield minimum component count. Texas Instrument series 51 microminiature logic circuits implement these equations without additional components.

This line of logic modules is noteworthy because of its small size, weight power consumption, and cost, along with high reliability. They are made by planar diffusion on monolithic silicon substrates and then hermetically sealed. Their low power consumption eases power supply demands and prevents dissipation problems. The relatively low maximum clock rate is of no consequence in this application.

Two Boolean equations of the form:

$$A = (P+R+S)\ I'K'N' + (J+K+M)\ O'Q'T'$$
$$B = (O+R+S)\ J'L'N' + (I+K+M)\ P'Q'T' \qquad \text{(V-9)}$$

can be mechanized with only seven series 51 modules. Together, their power dissipation is 80 mw. The compatibility of series 57 logic with the differential amplifiers selected for use eliminates the necessity for interface circuitry.

Sensor Temperature Control Amplifier SK92529

Several of the more straightforward circuits for temperature control in common use were investigated. Each was found to be deficient because of size, weight, power, reliability or economy. The SK92529 circuit uses cascaded integrated microminiature amplifiers of the Minuteman type to produce the low-level voltage gain and the switching action needed. The switching hysteresis of this circuit must be below 1 millivolt. A power gain driver stage follows which provides not only the power gain required but also negative bias to the "super alpha" or Darlington output circuit. This configuration may not be readily recognized as a Darlington pair. However, when using this type of circuit in a correct saturated mode it is unwise to tie the collectors together because tying them together increases the circuit dissipation as it is impossible to positively hold the output device in saturation due to the difference between V_{BEsat} and V_{CEsat}. Switching the ground side of the load is the most efficient and dependable approach, for two reasons. First, switching the high side of the load requires more power from the supply. Second, this increase in power from the supply must be dissipated within the circuitry, rather than the load.

Jet Driver SK92530

The outputs of the command logic to the jet drivers are inverted, i.e. 6 volts will appear on the output line when the logic output is zero. Power gain which is needed between the logic output and the load, can be combined with the needed logic inversion for component and power economy. This stage also provides the reverse bias for dependable switching operation. Diodes are used to create thresholds and to definitely bias the "super alpha" into cutoff. The "super-alpha" or Darlington connection may not be obvious. It is used for best current saturation mode operation. Here again the circuitry switches the ground side of the load.

Sensor Torquer Amplifier SK92531, 2 and 3

As the sensor torquer mechanical output is proportional to torquer current, it is essential to control this current rather than the voltage applied to the torquer. A resistor in series with the torquer develops a signal used for amplifier feedback. This type of feedback signal requires the amplifier to generate whatever voltage output is necessary to establish the proper current level. The output of the torquer amplifier is a pair of more conventional "super alpha" or Darlington stages used in "push-pull". The complementary pairs are used to provide both senses of current through the torquer load. The crossover distortion normally associated with this type of circuit is greatly reduced by the high ratio of open-loop to closed-loop gain. Signal voltage gain is obtained through use of the Minuteman solid state micromin amplifier. The necessary signal level transformation and power gain is attained by the circuit between the output stages and the solid state amplifier. A solid state switch is used to control the mode of operation of the ACS. This form of mode switching offers improved circuitry economy.

Axis Computer SK92531, 2 and 3

The axis computer includes no mechanical switches or choppers. Only solid state switching is used, which improves the size, weight, power, and reliability advantages of this system. The solid state switches are used to demodulate signals and to perform mode and signal switching. Differential or double-ended amplifiers and feedback networks are used throughout to provide the best possible offset and drift characteristics. This amplifier configuration provides twice the signal swing when used in a differential bridge and provides easily attainable full wave rectified signals. The absolute magnitude level sensing drive is fed to a single "one shot" multivibrator. This technique develops practically identical pulse widths for either phase of attitude error. Polarity sensitive steering of this pulse is accomplished by a phase sensitive switch and logic.

Differential amplifiers with nonlinear feedback networks, with output diodes for threshold are used to provide level sensing switches with minimum hysteresis. These switches are almost immune to null offset and drift. This switching scheme is used in several places in the design.

The logic stages included are necessary to properly steer the 17 ms pulse and to provide the proper mixing of the attitude and rate limit output signals. Mechanization of the "pseudo rate" circuit requires that a step voltage proportional to acceleration be applied to a first order lag network. The step must be delayed by a time roughly equal to the transport delay in the solenoid valve (5 ms). The delay is incorporated into the solid state switch which applies the step.

Changing from normal limit mode to extended limit mode is accomplished in a simple, reliable way. The gain changing switch is a dual emitter transistor driven in the inverted condition. This switch is incorporated in the first attitude amplifier. Emitter-to-emitter isolation in the off condition is about 100 megohms. The saturated impedance is about 100 ohms.

PACKAGING DESIGN

The objective of the packaging design study was to find the best combination of component arrangement and mounting for the AMU-ACS. Several approaches to the package design were considered, including 1) a combined electronic and sensor package or 2) separate modules for the electronics and sensors. The design factors considered were size, weight, reliability, fabrication techniques, maintainability, modular design, and cost.

One objective was to conserve sensor heater operating power. One way to do this would be to use the sensor mounting block as a heat sink for power components. As the gyro operating temperature is 180°F, operation of electronic components at this temperature would require severe derating. By mounting the electronic components in a separate module, derating can be avoided and the AMU structure used as a heat sink. If the sensors and electronics were mounted in a single package, the electronics module would have to be insulated from the sensors. To save this weight, it was decided to build the ACS sensors and control electronics modules in separate packages. This configuration offers the following advantages over the single package:

- Increased life and reliability for electronics parts.
- Improved sensor performance due to a more uniform structure.
- Simpler and cheaper fabrication.
- Lighter weight.

Drawings SK92540 and SK92538 show the installation, size, and design features of the sensor and electronics modules respectively.

The total average power dissipated by the electronic and sensor packages (after initial sensor warmup) is 27 watts. This requires that an area of slightly more than one square foot be provided on the AMU mounting structure to avoid exceeding the 25 watts per square foot heat dissipation limit. It is not considered practical to increase the size and weight of the individual packages so that they occupy this area. Consequently it will be necessary to set aside one square foot of mounting space on the surface of the AMU. A typical mounting configuration is shown in SK92540.

Sensor Package

The sensor package consists of a mounting block which contains the three sensors, a heater circuit power transistor, a terminal board, thermal insulating cover, mounting pad thermal insulators, a connecting cable and a connector.

The mounting block is made of magnesium. The placement of the sensors provides maximum utilization of space and minimum weight, consistent with mechanical strength and thermal uniformity. Index dowels are provided in the block to ensure sensor installation within 3 milliradians input axis rotation measured in the plane of the sensor mounting flange. Block mounting surfaces are to be machined so that sensor mounting flange perpendicularity errors are held to 2 milliradians or less.

Direct contact between the sensors and block allows free heat transfer between the sensors and block, which is used as a common heat sink. The three sensor heaters are connected in parallel with a single temperature controller to provide warmup and operating heat. Regulation of the block and sensor temperature is controlled by the internal heat sensor element of the center-mounted sensor, which may be at a slightly higher temperature than the other two sensors. Past experience has shown that a sensor configuration of this type has very good scale factor stability during heater temperature cycling.

The temperature gradients that may be present will affect only the "g" sensitive drift of the sensors. Since the environment in which the AMU-ACS is to operate is a zero "g" field, the increase in drifts should be negligible.

The sensors will be compensated for "g" insensitive drift after installation into the block and simulation of the operating environment. On this basis, the maximum compensated "g" insensitive drift will be 0.36 deg/hr RMS. The maximum drift stability value for "g" insensitive drift, for $0^{\circ}F$ storage is 0.38 deg/hr RMS. The sum of these values gives a maximum total drift of approximately 0.74 deg/hr, which is well within the drift requirement of 1 deg/hr. This is based on the assumption that the temperature gradients of the sensor block will remain the same from warmup to warmup. To ensure this, heat insulation between the sensor block and AMU mounting structure is provided by ceramic insulating pads located at the three block mounting pads. These insulators allow 15 watts dissipation (12 watts from the gyros, three watts from the control) into the AMU mounting structure, with the block temperature at $180^{\circ}F$ and the AMU mounting structure temperature at $73^{\circ}F$. With the AMU mounting structure at $67^{\circ}F$, approximately one watt is added for control. The three-watt control includes an allowance for unknown temperature fluctuations and may be reduced after heat fluctuation data is available. This will in turn reduce the heater power required. The insulating pad calculations were made under the assumption that, at the operating environment, the heat radiation and connection losses from the block are negligible and the block is at a constant $180^{\circ}F$.

To minimize the heater power required, a heat radiation shield is installed over the entire sensor block assembly. The sensor package heater power transistor is mounted on the block to supplement the heater element inputs. Other heat-dissipating components which do not cycle with the heater would add steady state heat to the block and require added control power at the maximum temperature differential condition. However, the heater power transistor operates only when heat is required; therefore, its heat dissipation can be added to that of the heater elements, thus decreasing the length of heater on time and total power required. Total sensor package weight is approximately six pounds.

Control Electronics Package

The control electronics package configuration was chosen for its combined features of reliability and efficient space utilization. Because of the required power levels of the circuits and discrete electrical components required, it is more efficient and reliable to use the cord-wood type modular construction than the thin film or printed circuit board type. The reliability and life of the electronics is a function of the heat dissipation cord-wood construction and lends itself to micromin conversion when this type of construction attains the reliability confidence needed.

The control electronics package consists of an assembly case which contains six modular electronic circuit cards, nine power transistors, two transformers, and three external electrical connectors. The total weight is approximately three pounds.

Each circuit card is an unpotted cordwood-stacked welded module consisting of resistors, capacitors, solid-state components and integrated circuitry. Each module or card is constructed to perform a certain function or functions. The card frame structure is made of two sheets of aluminum alloy formed to provide posts for mounting jig wafers on either side for component interconnection. The aluminum sheets, which are thin and flexible, are bonded together to form a laminated construction which provides vibrational damping in a visco-elastic material.

The small, low-powered components are installed in the center of the card and held in position by the jig wafers. Components such as transistors, high power resistors, and small transformers are mounted directly on the card frame. Component interconnections on individual cards are welded to solid bus strips.

Individual cards are dip- or brush-coated with epoxy varnish to bond the wafers to the card frame, secure the components and wires, and add structural strength and damping.

The welded modules are screwed directly to the base frame to provide a good heat transfer path. Interconnections between the individual welded modules are made by welded connections to solid bus strips along individual jig wafers on top of the cards. Individual module jig wafers, facilitate repair. Connections from the modules to the external connector pins are also welded. Welding the modules to the connector pins saves space and weight and increases reliability over the plug-in type module connection which has lower reliability because of the increased number of wire connections and sliding contacts.

The electronic assembly case is a rigid aluminum, L-shaped structure, open on four sides to provide ease of module, component, and wiring installation. Six mounting screws are used to secure the case directly to the AMU structure to provide good thermal conduction. To provide good heat conductivity from the electronic components to the case, the case cover is hermetically sealed and the module is back-filled with helium to a pressure of 5 psig. Helium has eight times the heat conductivity of air and will provide added heat dissipation capabilities. Individual module frame guides are contained on the sides of the cover to provide support and additional heat conductive paths. Heat generated in the individual module components is conducted to the card frame by mounting the higher power components either on or against the frame. Components mounted against the frame are secured to it by dip-coating with epoxy varnish to make a direct heat conductive path. Two large transformers and nine power transistors are mounted directly to the base for structural and heat conductivity purposes. The nine transistors include eight jet driver power transistors and one series generator power transistor.

A hermetically sealed package was considered to be more advantageous than an unsealed package. The sealed package offers good protection against effects of storage or unprotected handling along with better thermal properties.

It was felt these advantages outweighed the unsealed package's single advantage - accessibility in the field.

The external connectors on the control electronics package are Cannon HD series subminiature hermetically sealed rectangular header type. Featuring small size and weight, with good environmental characteristics, they are Minuteman approved parts designed to meet the Apollo requirements. The mating connector is provided with a potting boot, an environmental seal, and wire terminal kit for sealing and screw locks.

REFERENCE

V-1. Graybiel, A. "Orientation in Space With Respect to the Vestibular Function," Environ. Effects on Consciencciousness, Schaeffer, Karl E. (ed.), McMillan, 1962.

SECTION VI
RELIABILITY ENGINEERING

RELIABILITY REQUIREMENTS

The goal for the AMU failure rate is 125%/1000 hours (the equivalent of 1.25 failures per 1000 hours). That goal was apportioned among the major components on the basis of reliability predictions for those components. The apportionment was designed to give nearly equivalent margin between the prediction and goal for each component. Table 25 shows the final apportionment. Included is a column of apportioned reliability values calculated from the apportioned failure rates and an assumed 4-hour mission.

Table 25. Reliability Apportionment for AMU

Component	Apportioned Failure Rate (%/1000 hrs)	Apportioned Reliability
ACS and Controller	111.50	0.9955
Battery	5.00	0.9998
Reaction Jet Assembly	8.50	0.997
Total AMU	125.00	0.995

Apportionment for the ACS and Controller was further divided into specified goals in the individual equipment specifications. The ACS has a specified requirement that the failure rate must not exceed 50.0%/1000 hrs. Failure rate of the voice controller must not exceed 61.5%/1000 hrs.

RELIABILITY PREDICTION

Table 26 is a detailed reliability prediction for the ACS showing the distribution of failure rates among the ACS components. It can be used to calculate failure rate for specific functions of the ACS.

Table 26. Predicted Failure Rates of ACS Components

Component	Predicted Failure Rate (%/1000 hrs)
Pitch Torque Amplifier	0.607
Pitch Sensor	7.000
Pitch Axis Computer	0.774
Roll Torque Amplifier	0.607
Roll Sensor	7.000
Roll Axis Computer	0.774
Yaw Torque Amplifier	0.607
Yaw Sensor	7.000
Yaw Axis Computer	0.774
Sensor Temperature Control	0.616
Control Logic	0.280
Power Converter and Regulator	1.601
Reaction Jet Drivers	3.856
Emergency Controller Switch	0.100
Total ACS	31.596

There is no accurate reliability prediction for the voice controller as it is not yet sufficiently developed. The controller logic is well enough defined so that its failure rate is predicted to be 0.65%/1000 hrs. Two different voice recognition units have predicted failure rates of 18.1%/1000 hrs. and 16.5%/1000 hrs. Since these predictions are based on relatively less or definitive descriptions of the circuitry, factors were introduced to more realistically compensate for the complexity which is expected as these circuits are developed. Factors of 2 and 3 increase of complexity were used to arrive at predicted failure rates of 36.1%/1000 hrs. and 49.5%/1000 hrs., respectively.

The emergency controller failure rate is predicted to be 1.518%/1000 hrs. Its predicted reliability is 0.99994. The switch that controls engagement of the emergency mode increases failure rate of the AMU 0.1%/1000 hrs.

RECOGNITION ERROR RATE

A goal for recognition error rate of a voice recognition unit was proposed. A recognition error is a response to a sound other than a word that should stimulate response, or a lack of correct response to a word which should stimulate the unit to respond. A voice recognition unit should achieve a recognition error rate no greater than one error per 100 words spoken fluently at a rate of 120 words per minute by a trained astronaut. The recognition error rate of the two outputs "stop" and "cage" should be less than one error per 10,000 words.

EMERGENCY MODE

General

An ACS or voice controller failure will exhibit itself either by the presence of a hardover disturbance or by some loss of control. The astronaut will recognize a hardover in either translation or rotation almost instantly. He will notice a loss of command capability immediately upon giving a command and getting no response. If the limit cycle rate is slow, he might not notice a loss or degradation of attitude control for some time.

Because of the angular accelerations presently contemplated for the AMU and because of the danger of inadvertent acceleration in close quarters, any hardover must be considered an emergency. During the design of a system, these emergencies can be dealt with either by providing emergency control or by designing a system which is so reliable that no emergency control is required.

Detail

The minimum emergency control function is the disengagement of hardovers. The time required for the astronaut to recognize a malfunction and operate a conveniently situated disconnect device is estimated at 3/4 second. With maximum torque, a hardover in roll or pitch would result in an angular rate of about

45 deg/sec. A translational hardover would result in an unwanted velocity increment of 2 to 3 fps.

A number of provisions in addition to hardover disengagement are extremely desirable for emergency control. To prevent discomfort and possible disorientation (and the entanglement of a tether line if used), the astronaut would need some means of reducing his angular velocity. The minimum control which would provide this reduction is on-off angular acceleration control. To cooperate with tether line retrieval or to remove the incremental velocity due to a translational hardover would require as a minimum, manual translational control along one axis. The x axis would be preferred in order to provide retrothrust. If the hardover occurred along the y or z axis, the astronaut could use his control of angular accelerations to rotate himself 90 degrees in pitch or yaw and apply the proper direction of x axis acceleration for about 3/4 second to remove the unwanted velocity increment.

Loss of control will be manifested in one of three ways:

1. Attitude excursions beyond specified limits

2. Failure to respond to a rotational command (with otherwise good attitude control)

3. Failure to respond to a translational acceleration command (with good attitude control)

Except for a failure to provide braking thrust at close quarters, none of these conditions constitutes an emergency requiring instant action. On-off angular acceleration control and translational acceleration control would supply the needed emergency control functions as in the case of recovery from hardovers.

Based on the foregoing considerations, a reasonable minimum of emergency control would provide for the following functions:

1. Disengagement - This can be accomplished simply by removing jet operating power from the ACS electronics and supplying a signal to cage the gyros.

2. Angular Acceleration Control - This can be furnished by providing switches to operate the jets so as to produce couples about the body axes.

3. Translational Acceleration Control - This can be accomplished by providing a switch for each direction of translational control.

Given these three control functions, the astronaut would have control over attitude and attitude rates as well as translational acceleration. At the levels of angular acceleration presently contemplated, such manual control would be extremely tiresome. In case the malfunction was in the voice controller, any switching device which could turn the jets on and off could also apply and remove controller commands to the ACS electronics.

Considerations of astronaut fatigue and safety then suggest a limited re-engagement function which would restore jet operating power to the ACS electronics, remove the caging signal and the voice controller logic inputs, and connect the emergency controller logic. To permit the astronaut to perform these functions, a consideration of emergency controls was undertaken. In order to keep the emergency control as simple and reliable as possible, the following ground rules were established:

> Switches are preferable, from a reliability standpoint, to other types of manual input devices. Their strength and simplicity make them relatively immune to failure in the face of the severe environmental conditions likely to be encountered.
>
> Simple on-off control for rotational and translational thrusting is adequate for emergency purposes.

The emergency ACS disconnect switch should be highly accessible at all times.

A limited re-engagement function should be provided which substitutes the emergency controller for the voice controller with the ACS in automatic mode.

The emergency operating controls should be out of the way when not in use. When they are being used, a certain amount of inconvenience in reaching or using them can be tolerated.

It would seem desirable, from the standpoint of design simplicity and ease of operation, to locate all the emergency operating controls together in a group. Where this control "panel" should be located has been carefully considered. If it were located on the front of the astronaut's body or on the back of his forearm, the controls would be obstrusive when not needed. Therefore, a location on the side of the astronaut or on the backpack, low enough to be accessible to the right hand, seems indicated. The switch panel could be folded into the lower portion of the backpack when not in use; when needed, it could be extended, exposing the controls to the right hand of the astronaut.

The emergency disconnect should be a large push button or striker plate which the astronaut can reach easily and quickly at all times. By striking or pressing the button, the ACS is disconnected and the emergency control panel is extended for use. Folding the control panel back into its recess would reconnect the ACS, but a special reconnect switch could be provided on the emergency panel if needed, in which case the emergency controller would supply logic inputs to the ACS. It would seem logical to locate the emergency disconnect at the lower right side of the backpack, where it can easily be operated by the palm, fingers, or edge of the right hand. All of the emergency controls are thus located together in the same area. A second, redundant, disconnect switch can be located on the lower left side of the backpack so that an emergency disconnect can be made quickly by either hand.

Since the emergency panel is mounted to the backpack, the configuration of the switches on the emergency panel can be stated only in general terms until the size and shape of the backpack are definitely established.

For the sake of operational simplicity, the astronaut should be provided with three switches for controlling his motions in pitch, roll, and yaw. If toggle switches are used (and they can be recommended from the standpoint of simplicity and reliability), they can be oriented so the direction of their operation corresponds to the resulting motion, which is highly desirable. Similarly, another switch, appropriately oriented, should be used for translation in the x axis. The toggle switches should have large, easily manipulated handles that are operable in two directions (for plus and minus rotation or translation) and are spring-loaded to the center position. They should be arranged on the emergency panel so they do not interfere with each other.

A reliable mechanization can be obtained through use of a second coil in each thrust control valve. These coils would be operated directly from the AMU d-c power supply as controlled by the emergency controller command switches. Very little additional circuitry is required in either the electronics or the voice controller to accommodate the added mode switching and command signals.

Development of the two modes of emergency operation enhances the reliability and safety of the AMU. One mode gives the astronaut all the normal command and stabilization functions if the voice controller fails. The other gives him limited maneuvering capacity if the ACS fails. This gives the AMU a useful reliability of 0.9975 using apportioned reliability values. "Useful reliability" is the probability the AMU will provide normal command and stabilization functions by use of the voice controller or the emergency controller. The absolute reliability is 0.9995 by apportioned values. "Absolute reliability" is the probability the AMU will provide at least minimum maneuvering capability.

AMU SYSTEM RELIABILITY STUDY

A rather comprehensive system reliability trade-off study was made. In this study, "useful reliability" and "absolute reliability" were evaluated for each of several possible AMU systems. The variable among these systems is the redundancy used to protect the astronaut from AMU failures.

Table 27 is a summary of the results of this study. It shows the independence of the two measures of reliability.

Table 27. Summary of AMU System Reliability Study

System	Description	Useful Reliability		Absolute Reliability		Figure No.
		Value	Rank	Value	Rank	
A	Simple AMU with emergency controller	0.9975	5	0.9995	5	40
B	Simple AMU with independent manual emergency controller	0.9950	6	0.9998	4	41
C	Combination of A and B	0.9975	5	0.9998	4	42
D	AMU with duplication of each major component	0.99999	3	0.99999	3	43
E	System A with duplication of batteries and reaction jet assembly	0.9980	4	0.9999996	2	44
F	System A with duplication of batteries, reaction jet assembly, and ACS	0.9999957	2	0.99999987	1	45
G	System D with simple emergency controller	0.9999959	1	0.99999987	1	46

The study was predicated upon these assumptions:

1. The apportioned reliability goals for the various components are applicable.

2. Sufficient support equipment is available to completely check out each component (including the redundant ones) before leaving the space vehicle.

3. It is feasible to connect components as shown without introducing complex switching or decision circuitry that degrades reliability.

4. The failures of each component are independent of the performance of the other components.

5. Performance of each system fulfills all specified requirements.

System A, diagrammed in Figure 40, is the current concept of an AMU with a simple emergency controller. Its absolute reliability, R_a, is given by:

$$R_a = R_r R_s (R_p R_q + R_t - R_p R_q R_t) = 0.9995 \quad \text{(VI-1)}$$

where R_r, R_s, etc., represent the reliabilities of components r, s, etc., respectively. Its useful reliability, R_u, is given by:

$$R_u = R_q R_r R_s (R_p + R_t - R_p R_t) = 0.9975 \quad \text{(VI-2)}$$

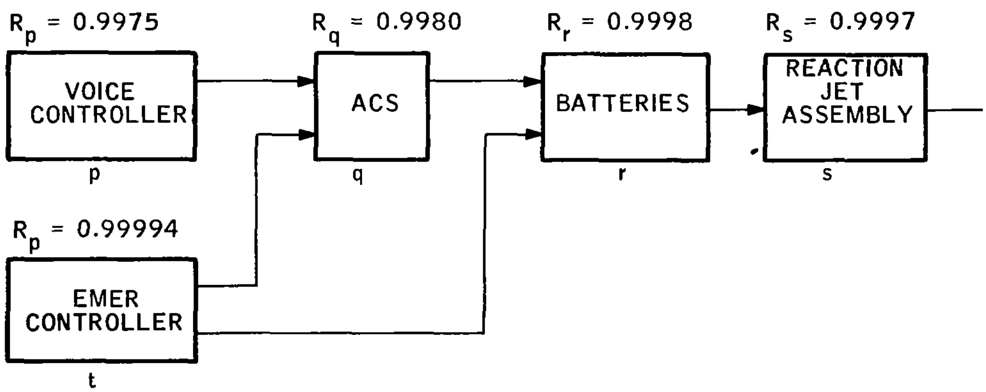


Figure 40. System A -Current AMU System with Simple Emergency Controller

System B is diagrammed in Figure **41**. It is the same as System A, except that a completely independent manual controller replaces the simple emergency controller. Assuming that an astronaut could operate the manual controller, a reliability goal was assumed for the independent controller. The absolute reliability of this system is higher than that of System A, but the useful reliability is lower. In this system, the absolute success function, S_a, is represented by the Boolean formula:

$$S_a = (p\,q\,r\,u + w)v \qquad \text{(VI-3)}$$

and the useful success function, S_u, is given by:

$$S_u = p\,q\,r\,u\,v \qquad \text{(VI-4)}$$

The two reliabilities are given by:

$$R_a = (R_p R_q R_r R_u + R_w - R_p R_q R_r R_u R_w)R_v = 0.9998 \qquad \text{(VI-5)}$$

and

$$R_u = R_p R_q R_r R_u R_v = 0.9950 \qquad \text{(VI-6)}$$

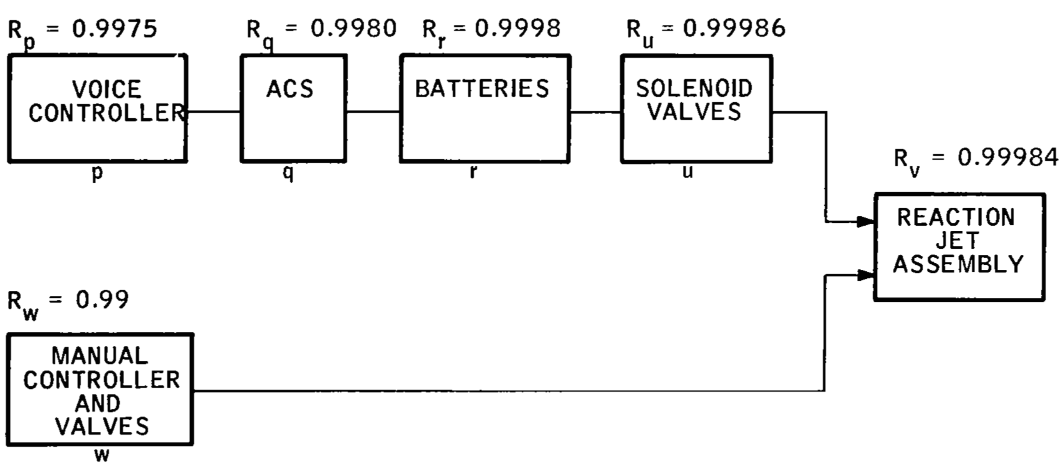


Figure **41**. System B-AMU with Completely Independent Manual Emergency Controller

Figure **42** is a diagram of System C. It is a combination of System A and System B. Its success functions are:

$$S_a = [(Pq + t)\, ru + w]\, v \tag{VI-7}$$

and

$$S_u = (p + t)\, q\, r\, u\, v \tag{VI-8}$$

Its reliabilities are given by:

$$R_a = R_v\ (1-R_w)\ [(R_pR_q + R_t - R_pR_qR_t)\,R_rR_u] + R_w \quad = 0.9998 \tag{VI-9}$$

$$R_u = R_qR_rR_uR_v\ (R_p + R_t - R_pR_t) = 0.9975 \tag{VI-10}$$

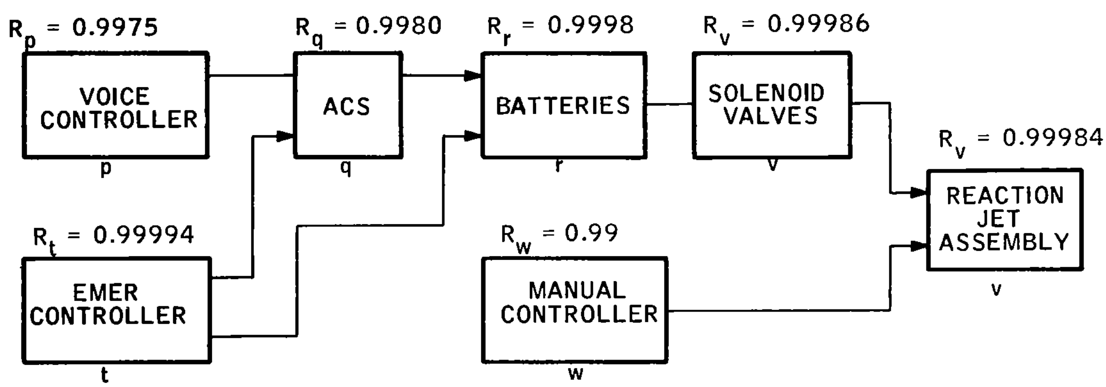


Figure **42**. System C - Combination of Systems A and B

Figure 43 is a diagram of System D, which achieves high reliability by duplication of each component. Implementation of this system may require switching or decision circuitry not shown. It is believed the extra circuitry will be simple enough so that it will not significantly degrade the reliability. Testing such a system may be difficult; however, it is important that the performance of each individual component be checked before each mission to achieve the desired reliability. The absolute and useful reliabilities are identical for this system. The success functions and reliabilities are given by:

$$S_a = S_u = (p_1 + p_2)(q_1 + q_2)(r_1 + r_2)(s_1 + s_2) \qquad \text{(VI-11)}$$

$$R_a = R_u = (R_{p_1} + R_{p_2} - R_{p_1} R_{p_2})(R_{q_1} + R_{q_2} - R_{q_1} R_{q_2})$$
$$(R_{r_1} = R_{r_2} - R_{r_1} R_{r_2})(R_{s_1} + R_{s_2} - R_{s_1} R_{s_2}) = 0.99999 \qquad \text{(VI-12)}$$

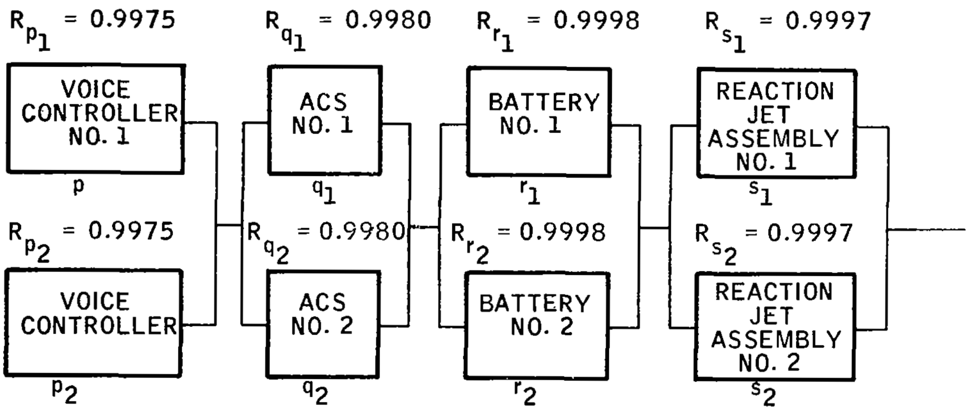


Figure 43. System D - AMU with Duplication of Components

System E, diagrammed in Figure 44, is System A with duplication of the batteries and the reaction jet system. This system achieves very high absolute reliability but its useful reliability is not much better than that of System A. Its success functions and reliabilities are given by:

$$S_a = (pq + t)(r_1 + r_2)(s_1 + s_2) \tag{VI-13}$$

and

$$S_u = q(p + t)(r_1 + r_2)(s_1 + s_2) \tag{VI-14}$$

$$R_a = (R_p R_q + R_t - R_p R_q R_t)(R_{r_1} + R_{r_2} - R_{r_1} R_{r_2})(R_{s_1} + R_{s_2} - R_{s_1} R_{s_2}) = 0.9999996 \tag{VI-15}$$

$$R_u = R_q(R_p + R_t - R_p R_t)(R_{r_1} + R_{r_2} - R_{r_1} R_{r_2})(R_{s_1} + R_{s_2} - R_{s_1} R_{s_2}) = 0.9980 \tag{VI-16}$$

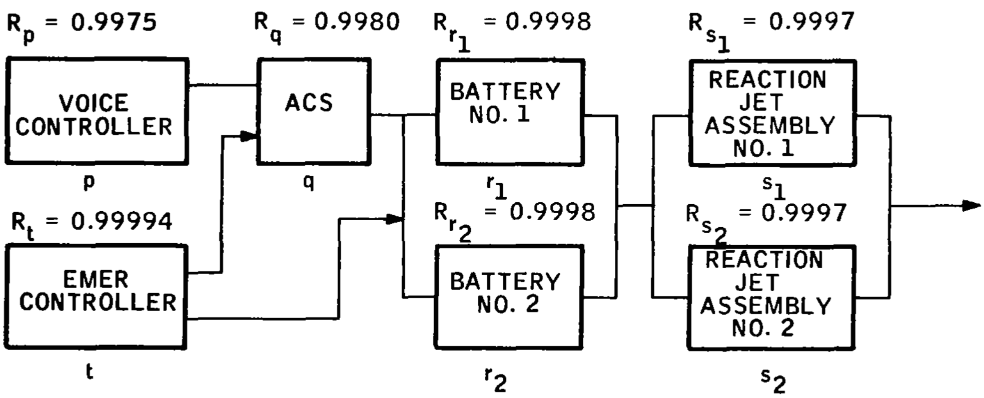


Figure 44. System E - System A with Duplication of Batteries and Reaction Jet Assemblies

System A, with duplication of the reaction jet assembly, the battery, and the ACS, is System F. It is significantly more reliable than the first five systems. Figure 45 is a diagram of System F. Its success functions and reliabilities are given by:

$$S_a = [p\,(q_1 + q_2) + t]\,(r_1 + r_2)\,(s_1 + s_2) \qquad \text{(VI-17)}$$

$$S_u = (p + t)\,(q_1 + q_2)\,(r_1 = r_2)\,(s_1 + s_2) \qquad \text{(VI-18)}$$

$$R_a = [R_p(R_{q_1} + R_{q_2} - R_{q_1} R_{q_2})\,(1 - R_t) + R_t]$$
$$(R_{r_1} + R_{r_2} - R_{r_1} R_{r_2})(R_{s_1} + R_{s_2} - R_{s_1} R_{s_2}) = 0.99999987 \qquad \text{(VI-19)}$$

$$R_u = (R_p + R_t - R_p R_t)(R_{q_1} + R_{q_2} - R_{q_1} R_{q_2}) R_{r_1} + R_{r_2} - R_{r_1} R_{r_2})$$
$$(R_{s_1} + R_{s_2} - R_{s_1} R_{s_2}) = 0.9999957 \qquad \text{(VI-20)}$$

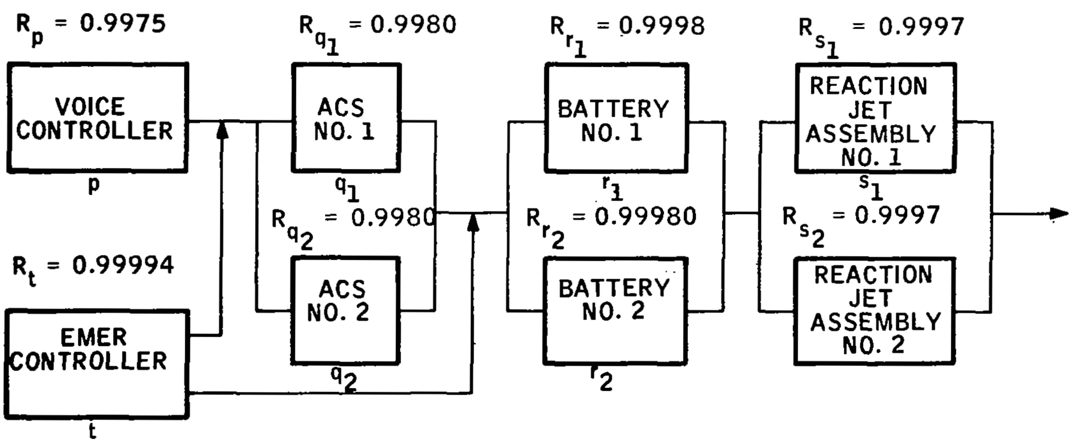


Figure 45. System F - System A with Duplication of ACS, Battery, and Reaction Jet Assembly

System G, diagrammed in Figure 46, is System D with a simple emergency controller added. It does not achieve much greater reliability than System F. Its success functions and reliabilities are given by:

$$S_a = [(p_1+p_2)(q_1+q_2) + t]\,(r_1+r_2)\,(s_1 + s_2) \qquad \text{(VI-21)}$$

$$S_u = (p_1+p_2+t)\,(q_1+q_2)\,(r_1+r_2)\,(s_1+s_2) \qquad \text{(VI-22)}$$

$$R_a = [(R_{p_1}+R_{p_2}-R_{p_1}R_{p_2})(R_{q_1}+R_{q_2}-R_{q_1}R_{q_2})(1 - R_t) + R_t)] (R_{r_1}+R_{r_2}-R_{r_1}R_{r_2})(R_{s_1}+R_{s_2}-R_{s_1}R_{s_2}) = 0.99999987 \qquad \text{(VI-23)}$$

$$R_u = [R_{p_1}+R_{p_2}+R_t+R_{p_1}R_{p_2}R_t - (R_{p_1}R_{p_2}+R_{p_1}R_t+R_{p_2}R_u)] (R_{q_1}+R_{q_2}-R_{q_1}R_{q_2})(R_{r_1}+R_{r_2}-R_{r_1}R_{r_2})(R_{s_1}+R_{s_2}-R_{s_1}R_{s_2}) = 0.9999959 \qquad \text{(VI-24)}$$

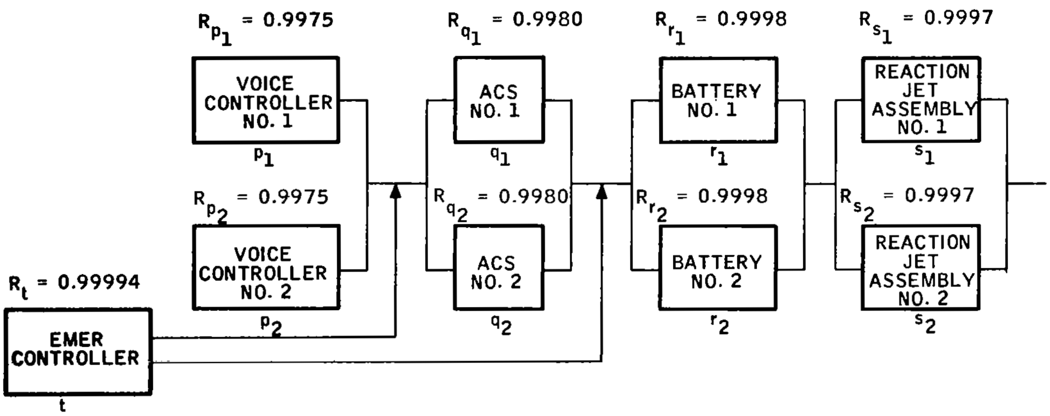


Figure 46. System G - System D with Emergency Controller

Other systems were considered briefly but were omitted from Table 27. Some were omitted because the resultant reliability was too low, others because their feasibility could not be evaluated at this time. One of these was a system using the current AMU backed up by a small AMU of very limited capability. Accurate estimation of the reliability of such a system is not possible until this system has been defined and its feasibility verified. However, rough estimates indicate that this system might yield high absolute reliability. Its useful reliability would depend upon the capability of the secondary AMU. Its weight should be less than other systems of Similar R_a. Its development cost would be higher. It is recommended that future studies of the AMU problem should evaluate such a system more thoroughly. A significant advantage may be gained because the assumption that failures of one component are independent of the performance of other components is more valid if the components in question are different. A common mistake in employing redundancy to improve reliability is use of components that fail simultaneously because of external conditions.

FAILURE INDICATING DEVICES

Failure indicating devices on the AMU may serve one or more of the following functions:

1. Warn of impending failure so that the astronaut may hasten to safety or take other appropriate measures

2. Warn of a maneuvering capability loss so that the astronaut may avoid situations requiring that capability

3. Help the astronaut to troubleshoot the AMU when it malfunctions, so that he can select the best emergency procedure

4. Provide psychological support to the astronaut by assuring him the AMU is operating correctly.

Failure indicators may introduce one or more of the following disadvantages to the AMU:

1. Be in the way so as to restrict the astronaut's visibility or mobility.

2. Distract the astronaut's attention from his task.

3. Reduce the reliability of the AMU.

4. Significantly increase the weight, power consumption, or fuel consumption of the AMU.

5. Failure of a failure indicator may cause a system failure or falsely limit mission activities.

Two classifications of failure indicators to be considered are: meters or other devices to measure some parameters of the AMU; and visual or audio "go no-go" indicators. An indicator may be used to check several parameters, in which case, it may or may not indicate what failed. There are also instances where two or more indicators are used on one parameter. For example, a light or buzzer may call the operator's attention to an out-of-tolerance condition that is also reported by a meter. The two or more devices may be functionally redundant, or they may be designed to call attention to the failure differently under different conditions.

The astronaut will be able to detect some failures as well without indicators as with them. For example, any change in the components associated with attitude stabilization will alter the deadband cycle about one or more axes. It is expected that the astronaut will very quickly notice a change in either amplitude or period of that cycle. If familiar with the operation of the AMU, he will be able to narrow the list of possible causes of a change, thus increasing his confidence in his ability to decide whether he should continue his mission, modify it, or immediately switch to an emergency procedure.

Although the astronaut will easily detect failures of his controller, it may not be until he gives a command and gets no response or the wrong response. That might create a real emergency. Diagnosing controller failures will require failure indicators or an exercise to find out what functions are defective. To determine command response, an exercise will require time and sufficient maneuvering space to allow the astronaut unimpeded movement to detect controller failure.

It is felt that the astronaut should have some form of feedback from his voice controller. Both audio and visual signals have been proposed. Audio signals might be a click, beep, or some other distinctive sound in the headphones. Visual signals might be a lamp or lamps in the helmet. The simplest signal would merely indicate that the voice recognition unit had sent a signal to the controller logic, or that the logic had responded to some signal. More sophisticated feedback systems might tell the astronaut more precisely what the controller is doing.

A feedback system would be a good failure indicating device as it could warn the astronaut of system failure to respond to a command before the command was complete. This would give him more time to take appropriate emergency action. Speed of detection could sometimes be the difference between an emergency and an inconvenience.

Failure diagnosis would be simplified by feedback from the controller to the astronaut. The need for maneuvering to check operation would be eliminated, as would the need for a complicated exercise to find out what functions were inoperative. Good failure diagnosis would allow the astronaut to assess his capabilities and decide what to do next.

The astronaut could use the feedback to occasionally check the controller, which should increase his confidence in the equipment.

Feedback would help the astronaut identify recognition errors by informing him the voice recognition unit had responded inadvertently, or had not responded. In event the unit failed to respond, the astronaut could repeat the command more carefully. In this manner he would ascertain if the failure is his or that of his equipment. Feedback would help him avoid unnecessary use of the emergency controller.

A fuel gauge is another failure-indicating device proposed. In addition to measuring the remaining fuel, a fuel gauge may warn the astronaut of some failure in the system that is causing consumption of fuel at an abnormal rate. The most likely cause of a complete AMU failure could occur in the reaction jet system, which has an apportioned reliability of 0.9997. A fuel gauge will reduce the possibility of a failure due to running out of fuel, and also alleviate the need for a large margin of fuel for each mission.

Several types of fuel gauge are possible. The simplest would give a warning signal to the astronaut when his fuel supply is low. Signals at a series of fuel levels (3/4, 1/2, 1/4, etc.) would be better. A sound with a pitch proportional to fuel level might be feasible. A visual gauge, which could be the simplest, should also be considered. An exotic fuel gauge would give a spoken output, as do some test equipment and aircraft instruments.

A device to notify the astronaut of a jet or jet driver amplifier failure would be useful. The simulation studies show that the difference in performance caused by an inoperative jet is small enough to possibly go unnoticed by the astronaut. However, it will change the direction and magnitude of linear acceleration. If a jet operates continuously, the AMU will maintain attitude stability but will accelerate linearly. Therefore, it will help the astronaut to avoid emergencies if he knows when a jet is not functioning correctly.

A battery monitor offers about the same advantages as a fuel gauge as it would warn the astronaut when he is low on battery power and when he is using battery power at an abnormal rate. It would also alleviate the problem of designing a battery with adequate power reserve.

Table 28 summarizes the initial study of failure indicators for an AMU. Thirteen different indicators were considered. Two important criteria of each were evaluated. The first criterion is the probability that the monitored component

Table 28. Summary of Failure Indicators for AMU

Failure Indicator	Probability of Failure of Monitored Component	Function Served	Remarks
Controller Feedback	0.0025	Warns of impending failure. Assists troubleshooting. Reassures astronaut.	Troubleshooting can be accomplished without the indicator, at the expense of time and maneuvering space.
Voice Controller Monitor	0.0025	Assists troubleshooting.	Too unwieldy and complex to serve other functions. Troubleshooting can be accomplished without the indicator.
Gyro Motor Monitors	Less than 0.00004 for 3 gyros	Warns of impending failure. Detects loss of function. Assists troubleshooting.	Change of ACS performance as gyro motor fails will serve nearly the same functions. Troubleshooting other than identifying affected axis won't help.
Gyro Temperature Indicators	0.000025	Warns of impending failure.	
Gyro Output Monitors	0.00063	Assists troubleshooting.	Troubleshooting other than identifying affected axis won't help. Affected axis can be identified without indicator.
Torque Amplifier Monitor	0.000073	Assists troubleshooting. Warns of loss of capability.	Troubleshooting won't help.
ACS Computer Monitor	0.000093	Assists troubleshooting	Troubleshooting won't help.
Power Inverter and Regulator Monitor	0.000064 0.00026*	Assists troubleshooting. May warn of impending battery failure.	Troubleshooting won't help. Monitoring of battery performance might be useful.
ACS Control Logic Monitor	0.000011	Assists troubleshooting.	Detailed troubleshooting won't help. The astronaut will know the ACS isn't working.
Jet Driver Monitor	0.00015	Assists troubleshooting. Detects loss of capability.	Detailed troubleshooting won't help. A jet monitor would be better. It is possible for one jet or jet driver to fail without the astronaut noticing it.
Jet Monitor	0.0003 (entire jet assembly)	Detects loss of capability. Assists troubleshooting.	It also will serve as adequate monitor for the jet drivers (see Jet Driver Monitor)
Fuel Gauge	Unknown	Warns of fuel shortage. Warns of abnormal fuel consumption rate.	Lack of fuel is very serious. The astronaut could carry reserve fuel. With a gauge, it would not be necessary to carry so much reserve.
Battery Monitor	0.0002	Warns of low battery. Warns of abnormal power consumption rate.	See fuel gauge.

*Includes probability of battery failure.

may fail. That is a very small number in all cases. The other criterion is the function the particular indicator may serve. Probably the most useful function is to warn of impending failure. Six of the indicators do that.

The three most useful indicators are the fuel gauge, the battery monitor, and the power inverter and regulator monitor. These indicators make known these impending critical failures: shortage of propellant and loss of battery power. These failure modes are classified critical because loss of power would leave the astronaut without means of controlling his motion, either angular or linear, thus putting his life in jeopardy. Such devices would also reduce tne problem of designing a fuel supply and a battery that achieve the desired reliability. The variance of fuel or battery consumption is estimated to be large, because of the variety of missions to be flown. It is therefore necessary to design a fuel supply and a battery with a large margin of capacity over the expected requirements. Gauges would eliminate the need for uncertain estimating of remaining flight capability, allow reduction of the margin of supply, and permit the astronaut to extend his mission if fuel supply and battery permit.

Before a decision can be made as to which indicators are best suited for use in the system, an investigation must be made of the feasibility and disadvantages. This will require enough design effort to permit evaluation of their convenience to the astronaut, their reliability, weight, power consumption, and cost. The choice of indicators can then be based upon the disadvantages, the functions served, the seriousness of the involved failures (see failure mode analysis, below), and the likelihood of the involved failures.

FAILURE MODE ANALYSIS

Table 29 summarizes the failure mode analysis of the ACS and the voice controller. The failure modes are defined in terms of AMU function. The components that might cause each failure mode are listed. The likelihood of each failure mode is evaluated as a failure rate, and each mode is classified by its severity.

Two failure rates are listed for each component and each failure mode. The total failure rate is the predicted failure rate of the component or the sum of the predicted failure rates of all the components which might cause that failure mode. This failure rate is a "worst case" evaluation. It would be the failure rate if all failures of the component caused that failure mode.

The contributory failure rate is a more realistic figure. It is the product of the total failure rate and the estimated fraction of failures that will cause the failure mode in question. The sum of the contributory failure rates of all the components that may cause a certain failure mode is the rate of occurrance of that failure mode.

The classification of failure mode by severity is critical (causes loss of the astronaut), major (causes mission abort), or minor (does not appreciably degrade performance as far as the mission is concerned). In all cases, it is assumed that the emergency controller is operative.

Table 29. Summary of Failure Mode Analyses of ACS and Voice Controller

Failure Mode	Contributing Components	Failure Rate: Total	Failure Rate: Contributing	Classification*
AMU does not respond to attitude error	A. Sensors (3)	21.000 %/1000 hrs	2.100 %/1000 hrs	Major
	B. Axis Computers (3)	2.322	1.161	
	C. Sensor Temperature Control	0.616	0.554	
	D. Control Logic	0.280	0.280	
	E. Power Inverter and Regulator	1.601	0.961	
	F. Reaction Jet Drivers	3.856	3.856	
	G. Emergency Controller	0.100	0.100	
		29.775	9.012	
AMU oscillates abnormally	A. Sensors (3)	21.000	2.100	Major, if amplitude is beyond deadband limits. Minor, otherwise.
	B. Axis Computers (3)	2.322	0.580	
	C. Sensor Temperature Control	0.616	0.031	
	D. Power Inverter and Regulator	1.601	0.320	
		25.549	3.031	
AMU uses propellant too rapidly	A. Control Logic	0.280	0.140	Critical, if astronaut doesn't recognize problem and tries to continue mission. Major, otherwise.
	B. Reaction Jet Drivers	3.856	1.928	
	C. Axis Computers	2.322	0.464	
		6.458	2.532	
AMU controls attitude, but not within desired deadband	A. Sensors (3)	21.000	6.300	Major, during rendezvous. Minor, otherwise.
	B. Axis Computers (3)	2.322	0.580	
	C. Voice Recognition Unit	50.000	5.000	
	D. Voice Controller Logic	0.650	0.065	
	E. Sensor Temperature Control	0.616	0.062	
	F. Power Inverter and Regulator	1.601	0.320	
		76.199	12.327	

*Assuming emergency controller is operative.

Table 29. Summary of Failure Mode Analyses of ACS and Voice Controller (Continued)

AMU accelerates linearly during attitude correction or control	A. Control Logic B. Reaction Jet Drivers	0.280 3.856 4.136	0.140 1.928 2.068	Minor, unless proximity to and velocity with respect to a large body makes collision dangerous.
AMU changes attitude slowly or at a constant rate	A. Sensors (3) B. Torque Amplifiers (3) C. Power Inverter and Regulator D. Voice Recognition Unit E. Voice Controller Logic	21.000 1.821 1.601 50.000 0.650 75.072	10.500 0.910 0.400 12.500 0.162 24.472	Major during rendezvous. Major if rate is excessive. Minor, otherwise.
AMU changes attitude at an increasing rate	A. Sensors (3) B. Axis Computers (3) C. Control Logic D. Reaction Jet Drivers	21.000 2.322 0.280 3.856 27.458	2.100 1.161 0.070 0.964 4.295	Major.
AMU does not respond to attitude commands	A. Torque Amplifiers (3) B. Sensors (3) C. Axis Computers (3) D. Control Logic E. Power Inverter and Regulator F. Reaction Jet Drivers G. Sensor Temperature Control H. Voice Recognition Unit I. Voice Controller Logic	1.821 21.000 2.322 0.280 1.601 3.856 0.616 50.000 0.650 82.146	1.366 2.100 1.161 0.280 0.901 3.856 0.554 25.000 0.325 35.603	Minor if only one axis is affected. Major if more than one axis is affected.

Table 29. Summary of Failure Mode Analyses of ACS and Voice Controller (Continued)

AMU does not respond to translation command	A. Voice Recognition Unit B. Voice Controller Logic C. Control Logic D. Reaction Jet Drivers E. Power Inverter and Regulator	50.000 0.650 0.280 3.856 1.601 56,387	25.000 0.325 0.280 3.856 0.901 30.422	Major.
AMU translates without command	A. Voice Recognition Unit B. Voice Controller Logic C. Control Logic D. Reaction Jet Drivers	50.000 0.650 0.280 3.856 54.786	12.500 0.162 0.140 0.964 13.766	Major.
AMU loses attitude stabilization during linear acceleration	A. Sensors (3) B. Axis Computers (3) C. Control Logic D. Reaction Jet Drivers E. Power Inverter and Regulator F. Sensor Temperature Regulator	21.000 2.322 0.280 3.856 1.601 0.616 29.675	2.100 1.161 0.140 1.928 0.400 0.554 6.283	Major.
AMU does not respond to cage command	A. Voice Recognition Unit B. Voice Controller Logic C. Sensors D. Axis Computers E. Torque Amplifiers F. Power Inverter and Regulator	50.000 0.650 21.000 2.322 1.821 1.601 77.394	5.000 0.065 2.100 0.232 0.910 0.400 8.707	Minor.
AMU cages inadvertently	A. Voice Recognition Unit B. Voice Controller Logic C. Axis Computers	50.000 0.650 1.821 52.471	5.000 0.065 0.182 5.247	Major.

SECTION VII
FUTURE PROGRAM RECOMMENDATIONS

The purpose of the study reported herein was twofold. First, it was intended to develop a suitable ACS for the AMU. Second, it was to define and report added developments associated with obtaining an operational system.

During the investigations of this study, several problems arose. In addition, several extensions of the work were defined. None could be explored, however, because they were beyond the defined scope of the study. These problems and study extensions, then, represent the subject matter for future programs which would help pave the way to a flightworthy AMU.

It is recommended that NASA consider the inclusion of these programs in their AMU program planning.

AMU RENDEZVOUS GUIDANCE

The Problem

Most rendezvous guidance schemes -- indeed most relative motion problems -- depend heavily on accurate sensing of the angular velocity of the line-of-sight. Brissenden and Lineberry* state that the threshold for pilot-controlled

*Brissenden and Lineberry "Visual Control of Rendezvous," IAS Paper No. 62-42, January 1962.

rendezvous should be 0.1 mr/second obtained by timing a target movement of 1 to 3 mr over a period of 10 to 30 seconds. Pennington and Brissenden* state that it is possible to derive a measurement of this accuracy from the observation of target motion in a star field under certain conditions.

The circumstances of AMU operation make it unlikely that the angular velocity threshold will be anywhere near as low as 0.1 mr/second. First, it has not yet been demonstrated that AMU rendezvous can use the technique of thrusting to keep the target stationary in a star field. If this technique cannot be used, an astronaut attempting to measure the angular velocity of the line-of-sight in AMU coordinates would have to subtract the target motion due to orbiting. This rate is about 1 mr/second or ten times the desired threshold. It seems likely that this rate would completely mask the desired information.

If the motion in a star field cannot be used, the astronaut will have to rely on devices attached to the AMU (optical devices, for instance). The AMU will be limit cycling in three axes with an amplitude of about 20 mr. If the limit cycle period is 5 seconds, for example, the peak rate will be about 24 mr/second. The astronaut will detect rates by noting angular differences at successive extremes of the limit cycle. If he can notice a change of 20 mr each cycle, he can detect about 4 mr/second after an interval of 5 seconds. Slower limit cycles would raise this threshold.

The natural quantity for the astronaut to sense is not rate but angular change. Since his rate-sensing performance under AMU conditions is considerably poorer than required by present guidance schemes, it would seem desirable to develop a system based on sensing angular differences.

*Pennington and Brissenden "Visual Capability of Pilots as Applied to Rendezvous Operations," IAS Paper No. 63-15, January 1963.

The guidance problem then is to develop a scheme which makes or computes velocity corrections in response to changes in line-of-sight angles. The solution must be compatible with AMU equipment and operating conditions.

Recommended Guidance Study

It is recommended that a more complete investigation be made of the guidance scheme conceived during the fixing of the attitude control requirements. Such a study would extend the scheme from the field-free case to a rotating coordinate system in the earth's gravitational field in order to ensure that Coriolis, centrifugal, and tidal accelerations do not overwhelm the correction capability of the scheme. The study would be limited to low earth orbits (100 to 500 nautical mile altitude) since these provide the most likely region for initial flights. The effects of small eccentricities (about 0.005) would also be studied.

Steering laws requiring the use of radars and/or high speed computers should not be considered. A design goal shall be established to eliminate the need for any data transmission from the spacecraft to the astronaut. An additional goal should be to avoid need for precessing the astronaut in a precise mode in order to permit him to solve the guidance problem.

The recommended study should investigate error effects including sensor errors, propulsion alignment and impulse errors, and errors in thrust timing to be sure that reasonable error magnitudes are compatible with the mission and to point out possible additional requirements.

The study should also examine means of minimizing propellant consumption. In particular, the possible reduction in propellant consumption, and possibly rendezvous time, that might be achieved by initially thrusting at some angle to the line-of-sight should be included. Subject to closing velocity and energy constraints, this part of the study would optimize the guidance scheme.

At present, the guidance scheme requires recalculation of the correction table (in terms of real time) after each correction. Methods for simplifying or mechanizing this procedure to assure that it will be compatible with AMU conditions and the capability of the astronaut should be evaluated. The astronaut's guidance tasks should be specifically defined. The goal should be to provide the astronaut with a self-sufficient guidance capability. It is recommended that this determination be made part of the study.

At present, no criterion exists in terms of orbital elements or initial conditions on range, range rate, and line-of-sight rates for deciding whether AMU rendezvous can be accomplished within the applicable time, energy, and guidance constraints. The recommended study should determine this criterion explicitly.

After error analysis and optimization results have been considered, the study should conclude by establishing the requirements of a subsystem to be integrated with the AMU which will accomplish the guidance tasks.

MOON SURFACE TRAVEL

The Problem

It appears that a reaction jet propulsion unit similar to the AMU will be useful or necessary for travel on the moon's surface. The question then arises whether one attitude control system can do both jobs.

Recommended Study Program

It is recommended that a program be instituted to determine the potential extension of the usage of the attitude control system developed under this program.

Such a program should study current estimates of lunar surface travel requirements and propulsion unit concepts with the purpose of defining missions and requirements. The specific differences in requirements for space travel and lunar surface travel would then be tabulated and the extent the space AMU will meet the expanded requirements would be evaluated. The feasibility of developing one ACS for both space and lunar surface travel would be established. In particular, potential advantages of a modular ACS concept which permits use of the one basic system in both environments should be defined. The program should produce a specific design recommendation.

CIRCUIT BREADBOARDS

The Problem

The work done during the study program provides NASA with a "paper design" of an attitude control system for an astronaut maneuvering unit. In the development of this design into flightworthy hardware, a number of problems arise. Among them are:

- Compatibility of circuit components
- Construction of a satisfactory vocabulary for a voice controller
- Evaluation of the response and control capabilities of a man using a voice controller
- Performance evaluation in dynamic simulations
- Determination of thermal characteristics and power consumption
- Determination of requirements imposed on the AMU by the ACS circuitry
- Integration with prototype AMU's
- Training of prospective users

All of these problems can best be attacked by building breadboards and making them work.

Recommended Breadboard Programs

It is recommended that two separate programs be instituted to build circuit breadboards -- one for the voice controller and one for the sensors and control electronics. The reason for the separate programs is that circuit development of the sensors and control electronics is further advanced and less uncertain than circuit development of the voice controller.

It is recommended that one breadboard of the sensors and control electronics be built to meet the functional requirements of Sections II and III of **Appendix A** at room temperature. It is not recommended that this first model be subjected to the more severe environmental requirements of Section II of **Appendix A.**

This device should be subjected to checks to ensure suitability for ordinary handling and to ensure that none of the circuits is unduly sensitive to temperature changes in the neighborhood of room ambient. After these checks, the devices would be delivered to NASA for further use in dynamic simulations and for studies of thermal characteristics. Other possible uses include voltage variation tests and integration tests with proposed reaction control systems.

The recommended program for voice controller breadboards would involve procurement of a speech recognition device, fabrication of the breadboards and experimentation. Experimentation should include studies of operator response and performance, vocabulary selection, and reliability analysis. At the end of the experimentation, the device would be delivered to NASA for their use in simulations, training, etc.

PRESSURE SUIT CHARACTERISTICS

The Problem

During the flexible man simulation, it was discovered that a model with a linear spring at the hip joint and no damping would oscillate persistently. Even when linear damping was included, attitude control performance was noticeably degraded.

A great deal of attention has been paid to the construction of full pressure suits for space use. Most of the work has attempted to provide greater freedom of movement rather than restricting this freedom.

During the state-of-the-art surveys, no investigations were found which would provide an experimentally verified mathematical model of the suit-man flexibility. Attempts to measure the spring constant at the hip by measuring the force-deflection characteristics of a man in a pressurized suit were unsuccessful.

Recommended Study

It is recommended that a study be made of the hip joint flexibility of suits presently contemplated for use on AMU missions.

The early portion of such a study should have as its aim the development of a mathematical model of the flexibility characteristics of the suit-man hip joint. Of all limb motions, only motions of the extended legs about the hip joint seem to have any pronounced effect on the location of the cm and the moments of inertia.

When the mathematical model has been completed, it would be programmed on an analog computer to study the interaction of the suit flexibility and control system activity.

The main purpose of this study would be to determine whether use of rate gyros is mandatory, or whether it would be worthwhile to immobilize the legs during rendezvous.

If this latter solution appears to be justified, a later study should be started to find sound methods of temporarily immobilizing the hip joint of a pressure suit.

DISCRETE COMMAND CONTROL

The Problem

Most control schemes which involve a man furnish him means of inserting continuous inputs with no more delay than the inherent lag of his nervous system. This study has designed a control system in which the man's inputs are quantized and in which succeeding inputs must await the completion of previous inputs. The scheme seems to afford an astronaut perfectly adequate control for both rendezvous and work tasks, but one can easily think of human control functions for which the scheme would not be well suited -- piloting an aircraft at high speed and low altitude or operating a bulldozer.

Recommended Study

It is recommended that a study be instituted to establish criteria for which manual discrete command control will yield satisfactory response. Anticipating that two effective bandwidth systems will be obtained, a minimum of two control schemes should be considered. They are:

1. Several suitable discrete command levels for each controlled function with a controller suitable for simultaneous input in all controlled axes.

2. Several suitable discrete command levels for each controlled axis with a controller suitable for command input in only one control axis at a time.

APPENDIX A

SECTION I

REQUIREMENTS FOR THE ASTRONAUT MANEUVERING UNIT ATTITUDE CONTROL SYSTEM

1.0 SCOPE

1.1 Requirements

This specification defines requirements for an attitude control system (ACS) for an astronaut maneuvering unit (AMU). It also includes requirements for a controller to be used by the astronaut in commanding translational or rotational movement. Pertinent data for related subsystems is given.

1.2 Statement of the Problem

Future space missions will require astronauts to leave their spacecraft and travel to a target. Once there, they will perform some work task, inspection, assembly, etc. When their work is complete, they will return to their spacecraft.

For the foreseeable future, astronauts will perform this maneuver by orienting mass expellant jets and applying translational thrust. During an orbital transfer, translational thrust also will be required for error correction.

Proper orientation of translational jets and error sensors implies attitude control and hence moment-producing devices. So long as mass expellant jets are required for translational thrust, it seems most unlikely any other moment-producing devices will be attractive on a weight-size-power basis.

1.3 Constraints

1.3.1 In view of the expected translational thrust misalignments, it is most likely that an automatic attitude control system will be required.

1.3.2 The human eye (plus sighting devices) will probably be the only error sensor available for line-of-sight angle sensing during the rendezvous maneuver. Prior to and during translation, the astronaut must have as large a visual field as practicable, to permit searching for and locking on the target. During search, the scanning process should be facilitated by attitude control, while during translation attitude stabilization will be necessary to prevent loss of visual contact with the target.

1.3.3 After arrival at the target, the astronaut must have attitude control capability in order to orient himself properly for performance of his tasks. After attitude orientation at the target the astronaut must be provided with mechanical body restraint to permit application of arm and hand forces on the tools being used. He should have maximum freedom of arm motion and finger flexibility to successfully manipulate tools as needed. No work tasks will require counteracting moments produced by the ACS, except in the movement of tools or material.

1.3.4 The ACS should at all times prevent angular rates from exceeding certain maximum values, in order to prevent loss of orientation and onset of confusion on the part of the worker. In the event high rates (or tumbling) occur, the astronaut should be equipped with a means for rapid recovery.

1.3.5 During translation, the limit cycle should not be annoying to the astronaut in respect to frequency and amplitude of cycling, or restrict his capability in solving the guidance problem.

1.3.6 Size, Weight, Power -- The ACS must be compatible with life support, communications, thrust propulsion system, available batteries, and imposed weight limitations.

2.0 APPLICABLE REFERENCES

2.1 NASA Contract NASw-841

2.2 Test Conditions -- Functional, electrical, and mechanical design must be compatible with the space environment and AMU mission and configuration.

3.0 ATTITUDE CONTROL SYSTEM DESIGN REQUIREMENTS

3.1 General

3.1.1 The function of the ACS will be to control attitudes and attitude rates of of an astronaut wearing a backpack AMU during rendezvous and performance of work tasks.

3.1.2 The ACS will be part of an AMU which will comprise, in addition, a life support system, a bio-electric structural interface, a translational propulsion system, a controller, power supplies, and a communications system.

3.1.3 The ACS shall consist of attitude sensing, valve driving and signal processing circuitry.

3.1.4 The ACS shall operate in three modes: synchronous, normal limit operate and extended limit operate -- and shall be compatible with an emergency mode.

3.1.4.1 Synchronous Mode -- The gyros are held at their nulls, and jet actuation is prevented so that no large rotations would be required if switched to either operate mode.

3.1.4.2 Normal Limit Operate Mode -- The ACS will stabilize the astronaut and maintain him in the desired attitude within the tolerances of Paragraph 3.2.1. Upon actuation of the controller, the ACS shall provide a means of rotating the astronaut in either direction about the x, y, or z axis. The astronaut should have a choice of three rates: high speed for gross adjustments, and two slower rates for fine attitude control. The astronaut shall also have the ability to command two levels of translational acceleration along both directions of his principal axes. For rotation, the controller will command rates such that when the command is removed, body motion will stop without counter-command. For translations, the controller shall command acceleration such that when the command is removed, so are the translational forces.

3.1.4.3 Extended Limit Operate Mode -- This is the same as normal limit operate mode, except that attitude tolerances are those of Paragraph 3.2.2 instead of 3.2.1.

3.1.4.4 Emergency Mode -- In event of an ACS malfunction resulting in loss of control or undesirable accelerations, the astronaut shall be provided with means of immediately disengaging the ACS, of stopping the inadvertent motions produced by the malfunction, and of engaging an emergency minimum-performance system to permit return to the base vehicle.

3.1.5 The system will be similar in function to the Mercury ASCS, Gemini ACME, and Apollo SES.

3.1.6 The ACS sensors and control electronics shall weigh less than 10 pounds and consume less than 360 watts maximum. Volume of the ACS sensors and control electronics shall be less than 250 inches^3.

3.1.7 Reliability goal for the ACS shall be 0.9980 for a four-hour mission. Reliability is defined as the probability the ACS fulfills the performance requirements listed in Paragraphs 3.1.4.1 and 3.1.4.2 and defined in Paragraph 3.2 without resort to emergency modes of operation.

3.2 Detail

An inertial coordinate system is established with the X-axis in an arbitrary direction, the Y-axis at right angles and the Z-axis to form a right-handed set. A set of right-handed principal axes (x, y, z) is established in the AMU -- the x-axis pointing in the direction of main translational thrust, y-axis "out the right wing", and the z-axis approximately head-to-toe. The inertial system (X, Y, Z) is rotated into the AMU (x, y, z) system by first a yaw angle (ψ) about the Z-axis, a pitch angle (θ) around an intermediate pitch axis, and a roll angle (ϕ) around the x-axis.

3.2.1 Attitude Control Requirement for Rendezvous

3.2.1.1 Command attitudes must be continuously variable through 360 degrees in either direction around the x, y, z axes.

3.2.1.2 In Normal Limit Operate, with no thrust applied, the ACS shall hold set point angles within the following limits (including limit cycle amplitude) for a period not to exceed 20 minutes:

Yaw	$\pm 1°$
Pitch	$\pm 1°$
Roll	$\pm 3°$

3.2.1.3 In Normal Limit Operate, with $\pm$ x axis thrust applied and the center of mass within the limits given in Paragraph 5.3, the ACS shall hold the set point angles within the following limits (including limit cycle amplitude):

Yaw	$\pm 5°$
Pitch	$\pm 5°$
Roll	$\pm 7°$

3.2.1.4 In Normal Limit Operate, with $\pm$ y or $\pm$ z axis thrust and the center of mass within the limits called out in Paragraph 5.3, the ACS shall hold the set point angles within (including limit cycle amplitude):

Yaw	$\pm 5°$
Pitch	$\pm 5°$
Roll	$\pm 7°$

3.2.1.5 With the ACS in Normal Limit Operate, if a new attitude is commanded, the ACS shall command attitude rates within the following limits:

Yaw	< 40 deg/sec
Pitch	< 40 deg/sec
Roll	< 40 deg/sec

3.2.1.6 Angular acceleration shall not exceed 1.5 rad/sec^2 in roll and pitch and 0.75 rad/sec^2 in yaw.

3.2.2 Attitude Control Requirements for Work Tasks

3.2.2.1 Command attitudes must be continuously variable through 360 degrees in either direction around the x, y, and z axes.

3.2.2.2 In Extended Limit Operate, with no thrust applied, the ACS shall hold set point angles within the following limits (including limit cycle amplitude):

Yaw	$\pm 10°$
Pitch	$\pm 10°$
Roll	$\pm 10°$

3.2.2.3 In Extended Limit Operate, with the $\pm$ x axis thrust applied and the center of mass within the limits given in Paragraph 5.3, the ACS shall hold the set point angles within the following limits (including limit cycle amplitude):

Yaw	$\pm 10°$
Pitch	$\pm 10°$
Roll	$\pm 10°$

3.2.2.4 In Extended Limit Operate, with ± y or ± z axis thrust and the center of mass within the limits called out in Paragraph 5.1.1, the ACS shall hold the set point angles within:

Yaw	±10°
Pitch	±10°
Roll	±10°

3.2.2.5 With the ACS in Extended Limit Operate, if a new attitude is commanded, the ACS shall command attitude rates within the following limits:

Yaw	< 40 deg/sec
Pitch	< 40 deg/sec
Roll	< 40 deg/sec

3.2.2.6 Angular accelerations shall not exceed 1.5 rad/sec^2 in pitch and roll and 0.75 rad/sec^2 in yaw.

4.0 DESIGN REQUIREMENTS - CONTROLLER

4.1 General

4.1.1 The controller shall be designed to allow the astronaut to command translational or rotational movement, through control of the translational propulsion system.

4.1.2 The controller will be part of an AMU which will comprise, in addition, a life support system, a bio-electro-structural interface, a translational propulsion system, an attitude control system (as defined in Paragraph 3.0), power supplies, and a communication system.

4.1.3 The reliability goal for the controller shall be 0.9975 for a four-hour mission. Reliability is defined as the probability the controller will perform the function described in Paragraph 4.1.1 without resorting to emergency modes of operation.

4.2 Detail

4.2.1 The operator shall be provided with an emergency ACS release in the event of a malfunction. The release control shall be continuously accessible and simple to operate, requiring only one short movement to actuate it. The emergency control shall not be located where it can interfere with normal operational procedures, and shall not be liable to inadvertent actuation.

4.2.2 The controller shall be mechanized using voice actuation.

4.2.3 A basic single voice command sequence shall result in a controller output command duration of one second.

4.2.4 Sustained controller command output shall be obtained with a verbal "repeat command instruction".

4.2.5 Provision shall be included for correcting (or changing) a command at any time before the command has been executed.

4.2.6 A single word "stop" command shall be included that will remove all commands from the system. The translational system shall revert to Coast mode, and the ACS shall revert to attitude hold using the reference which existed at the time the "stop" command was given. No release function shall be necessary for the system to accept new commands after the "stop" command has been given.

4.2.7 An "ACS off" command shall be provided. System power shall remain on in this mode. Attitude gyros shall be in an attitude synchronous mode of operation. Reaction jet operation must be prevented. Normal operation should resume any time a normal command sequence is given. Attitude reference shall be that existing at the time of the command, provided that angular rates are less than 20 deg/sec.

4.2.8 Commands shall consist of the following:

4.2.8.1 Translational

4.2.8.1.1 Jet commands in the fore and aft direction, up or down, and to either side shall be mechanized.

4.2.8.1.2 Two thrust level commands shall be included.

4.2.8.1.3 Mechanization shall be such that a "Jet on" time in response to a single command sequence shall be obtained as follows:

Axis	Low Thrust Mode (sec)	High Thrust Mode (sec)
Fore and aft	0.075	1
Up and down	0.075	1
Side	0.075	1

4.2.8.1.4 For sustained commands, the low thrust controller output shall be at a 1-cps pulse rate. The high thrust controller output shall be constant for the duration of the sustained command.

4.2.8.2 Rotational

4.2.8.2.1 Jet commands in pitch, yaw, and roll and in each sense (plus and minus) shall be mechanized.

4.2.8.2.2 Three levels of attitude rate commands shall be included.

4.2.8.2.3 Mechanization shall be such that attitude rates shall be obtained as follows:

Axis	Precision Mode (deg/sec)	Low Rate Mode (deg/sec)	High Rate Mode (deg/sec)
Pitch	0.15	3	20
Yaw	0.15	3	20
Roll	0.15	3	20

4.2.8.2.4 A low (guidance rendezvous) and a high (work task) limit cycle amplitude mode switching capability upon command shall be included.

4.2.9 In the event of a malfunction in the ACS or propulsion systems necessitating disengagement of the ACS, the astronaut shall be provided with a means for recovering from inadvertent tumbling. Because the astronaut may have difficulty determining the direction and amount of his tumble, recovery shall be facilitated by effecting recovery in one plane at a time. Emergency controls, reasonably accessible and easy to operate, shall be specified for tumbling recovery, rotation, and translation with the ACS disengaged. The emergency controls may be located wherever practicable, and operated by any suitable means.

Since the emergency controls may be an integral part of the translational propulsion system, design responsibility shall be limited to specification only. Compatibility with the ACS and controller shall be of major concern. The ACS design shall include all appropriate emergency mode circuitry.

5.0 DESIGN DATA

The ACS and controller design shall be based on related subsystem characteristics defined as follows:

5.1 Human Factors

5.1.1 Arm movement limits are as defined in Figure I-1.

5.1.2 No head movement inside the helmet occurs.

5.1.3 Visual capability is as defined in Figure I-2.

5.2 Thrust Propulsion System Characteristics

5.2.1 The basic jet configuration is as given in Figure I-3.

5.2.2 Nominal thrust rating of each reaction jet shall be 15 pounds.

5.2.3 Reaction Jet Characteristics

5.2.3.1 Hydrogen Peroxide System

5.2.3.1.1 Valve dead time = 10 to 15 ms for turn-on and turn-off.

5.2.3.1.2 Thrust rise time expressed as a single lag time constant measured from initiation of valve movement:

T. R. = 20 ms for hot catalyst beds.
T. R. = 80-100 ms for cold catalyst beds.

5.2.3.1.3 Thrust decay time expressed as a single lag time constant measured from initiation of valve movement:

T. D. = 20 ms

5.2.3.1.4 Thrust amplitude shall be within 10 percent of nominal.

5.2.3.1.5 Valve current design level shall be 1.0 ampere. Input impedance design level shall be 30 mh and resistance 28 ohms. Valve pull-in shall occur at 0.5 ampere maximum and drop-out at 0.1 ampere minimum.

5.2.3.2 Bi-propellant System

5.2.3.2.1 Valve dead time = 5 ms for turn-on.

5.2.3.2.2 Valve dead time = 1 ms for turn-off.

5.2.3.2.3 Valve rise and decay time = 2 ms.

5.2.3.2.4 Thrust rise time expressed as a single lag time constant measured from initiation of valve movement:

T. R. = 0.0058 second

5.2.3.2.5 Thrust decay time expressed as a single lag time constant measured from initiation of valve movement:

T. D. = 0.0058 second

5.2.3.2.6 Minimum impulse obtainable is equal to rated thrust times 0.0173 second.

5.2.3.2.7 Thrust amplitude shall be within 10 percent of nominal.

5.2.3.2.8 Valve current design level shall be 1.0 ampere. Input impedance design level shall be 30 mh and resistance 28 ohms. Valve pull-in shall occur at 0.5 ampere maximum and drop-out at 0.1 ampere minimum.

5.3 AMU Configuration

Astronaut, suit, and AMU (backpack) configuration is as follows:

5.3.1 Mass

	Maximum (slugs)	Minimum (slugs)
Astronaut	5.09	5.09
Suit	0.65	0.65
AMU	5.90	3.70
Total	11.64	9.44

5.3.2 Astronaut Positions

Mass distribution, and mass center and joint locations for the astronaut plus suit for the positions upon which the study shall be based are given in Figure I-4.

5.3.3 AMU Location

The position of the mass center of the AMU relative to the astronaut is given in Figure I-5.

5.4 Long Tether Line Acceleration

The ACS design must be compatible with accelerations up to 8 fps^2 caused by a long tether line attached to the AMU. The line of action of the acceleration shall be considered to pass through the total center of mass for position 1 of Figure I-4 and Figure I-5, and parallel to the x-axis.

It is assumed that a harness attached to the AMU will be utilized to constrain tether line forces through the total center of mass location as a means of minimizing associated angular accelerations. Tether line forces shall be directed nominally "forward" in all instances.

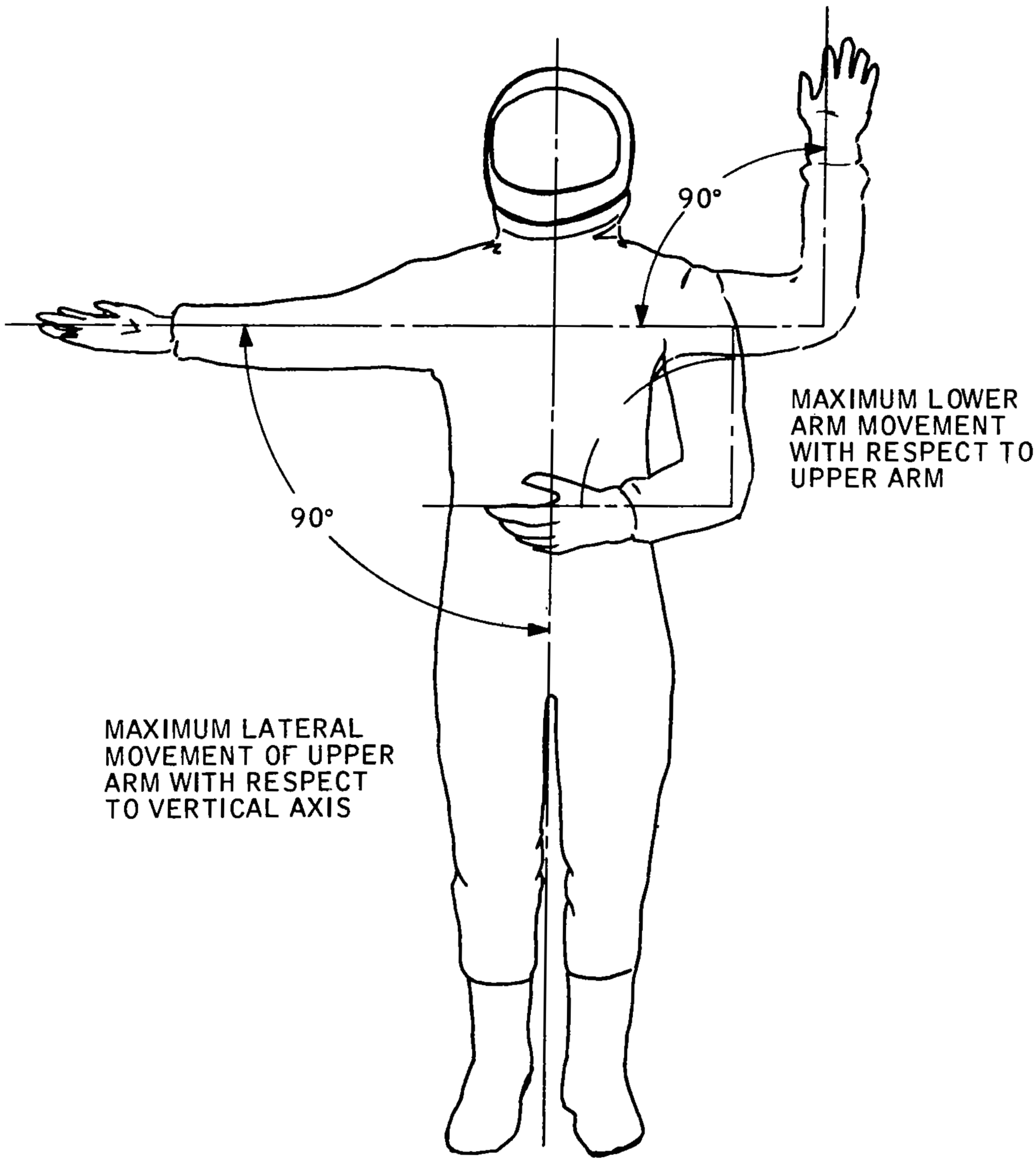


Figure I-1. Arm Movement Limits

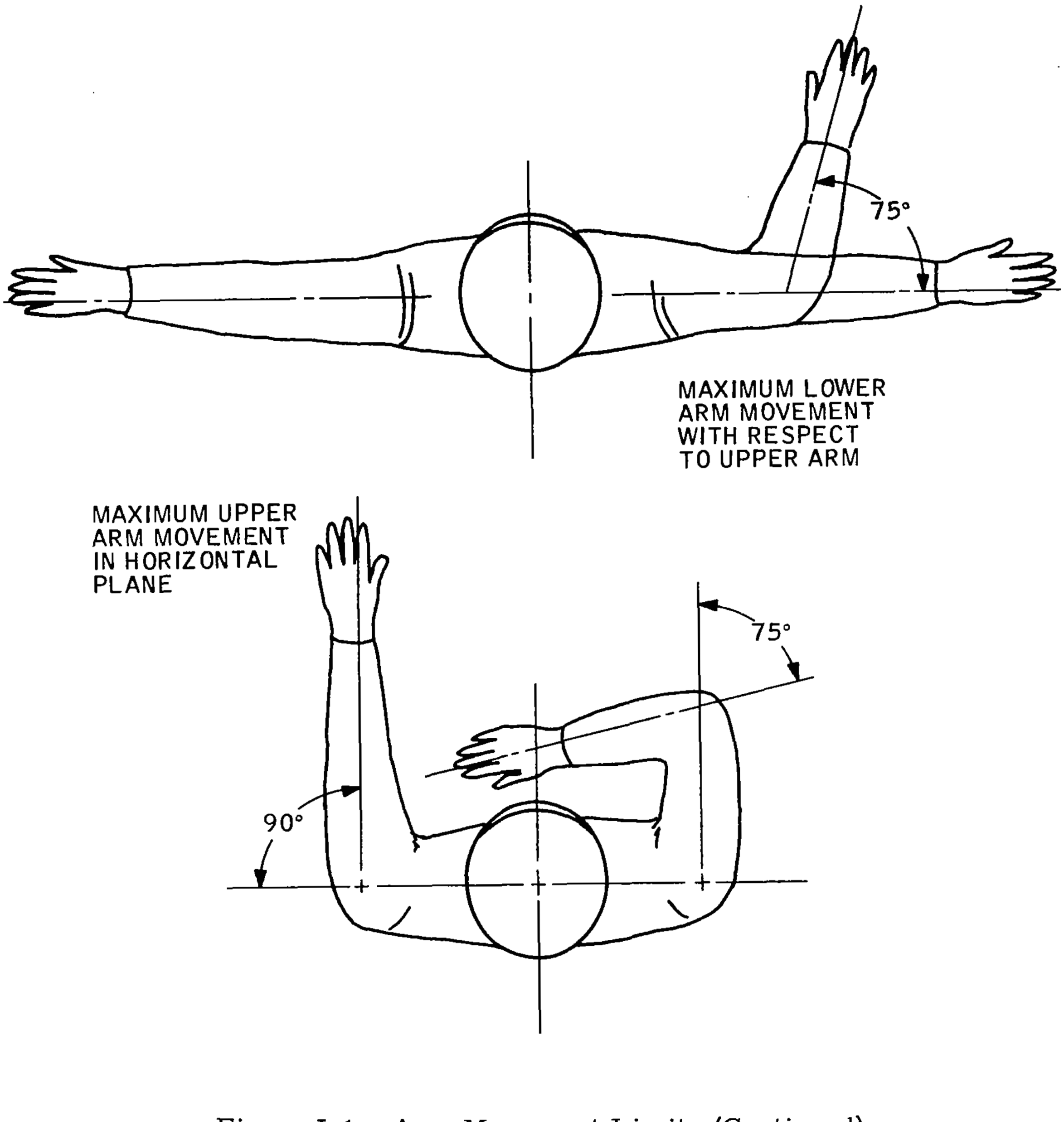
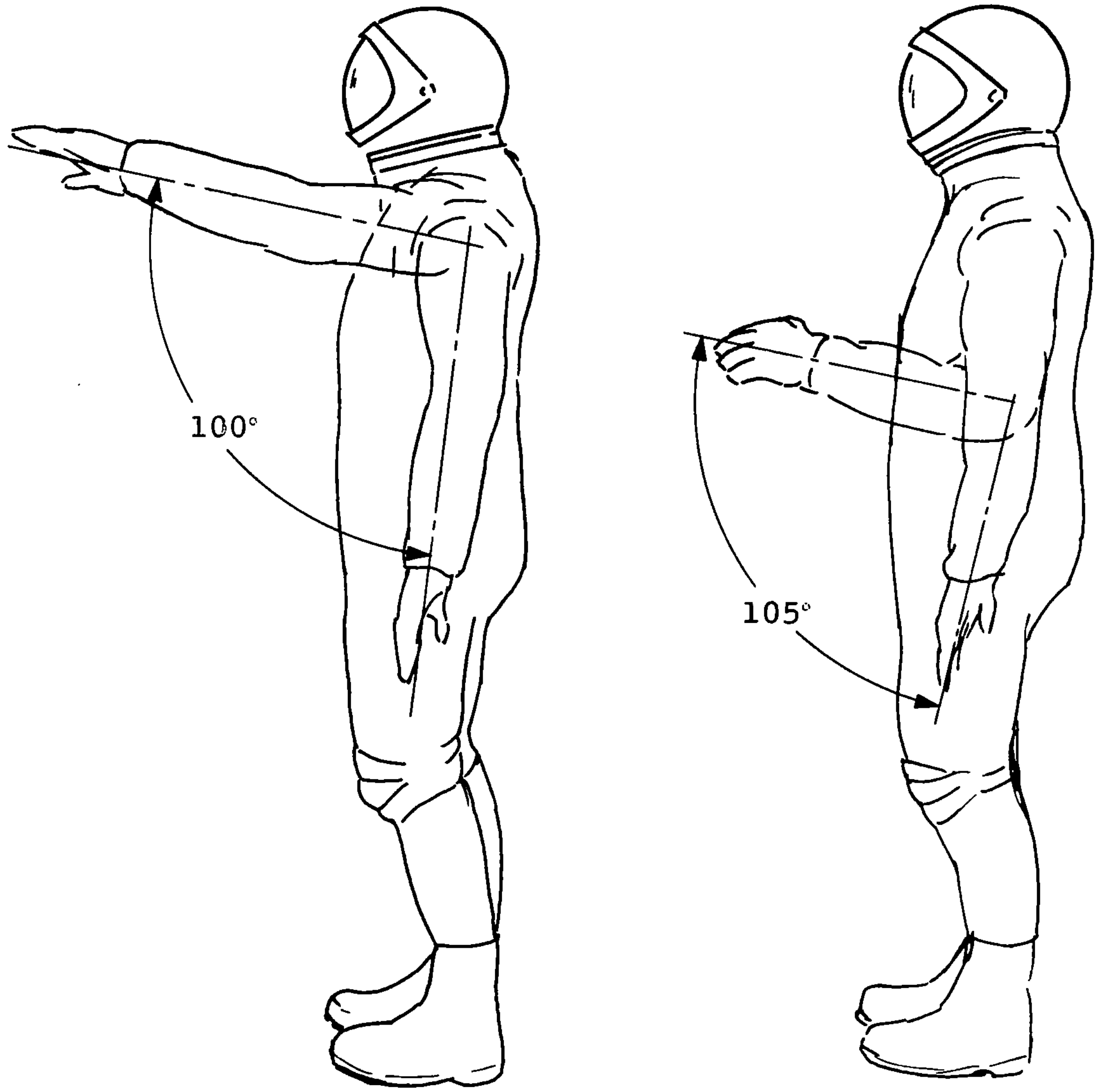


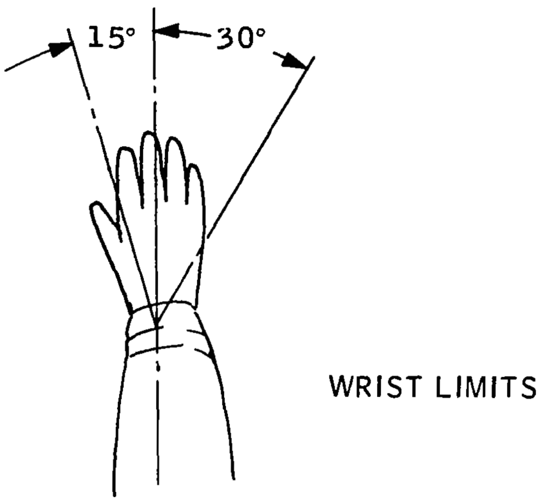
Figure I-1. Arm Movement Limits (Continued)



MAXIMUM FORE-AND-AFT MOVEMENT OF UPPER ARM WITH RESPECT TO VERTICAL AXIS

MAXIMUM LOWER ARM MOVEMENT WITH RESPECT TO UPPER ARM

Figure I-1. Arm Movement Limits (Continued)



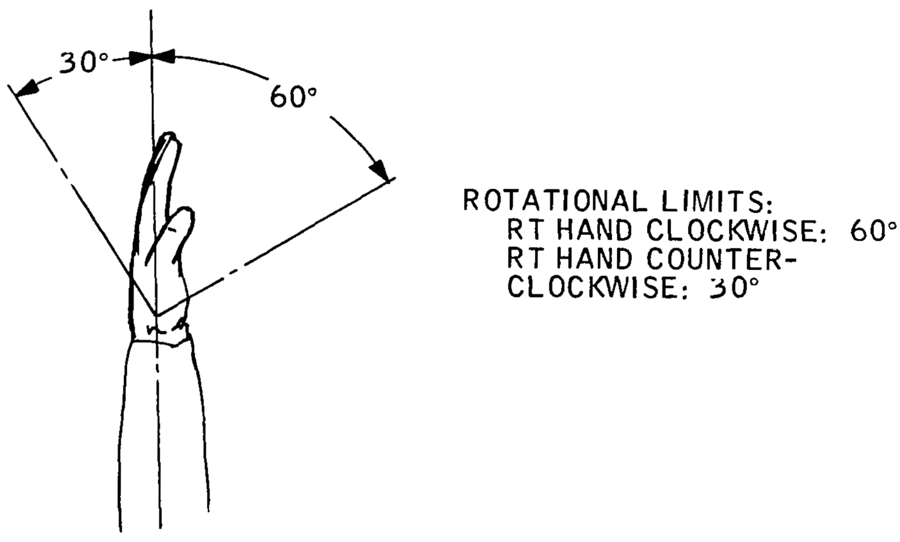


Figure I-1. Arm Movement Limits (Continued)

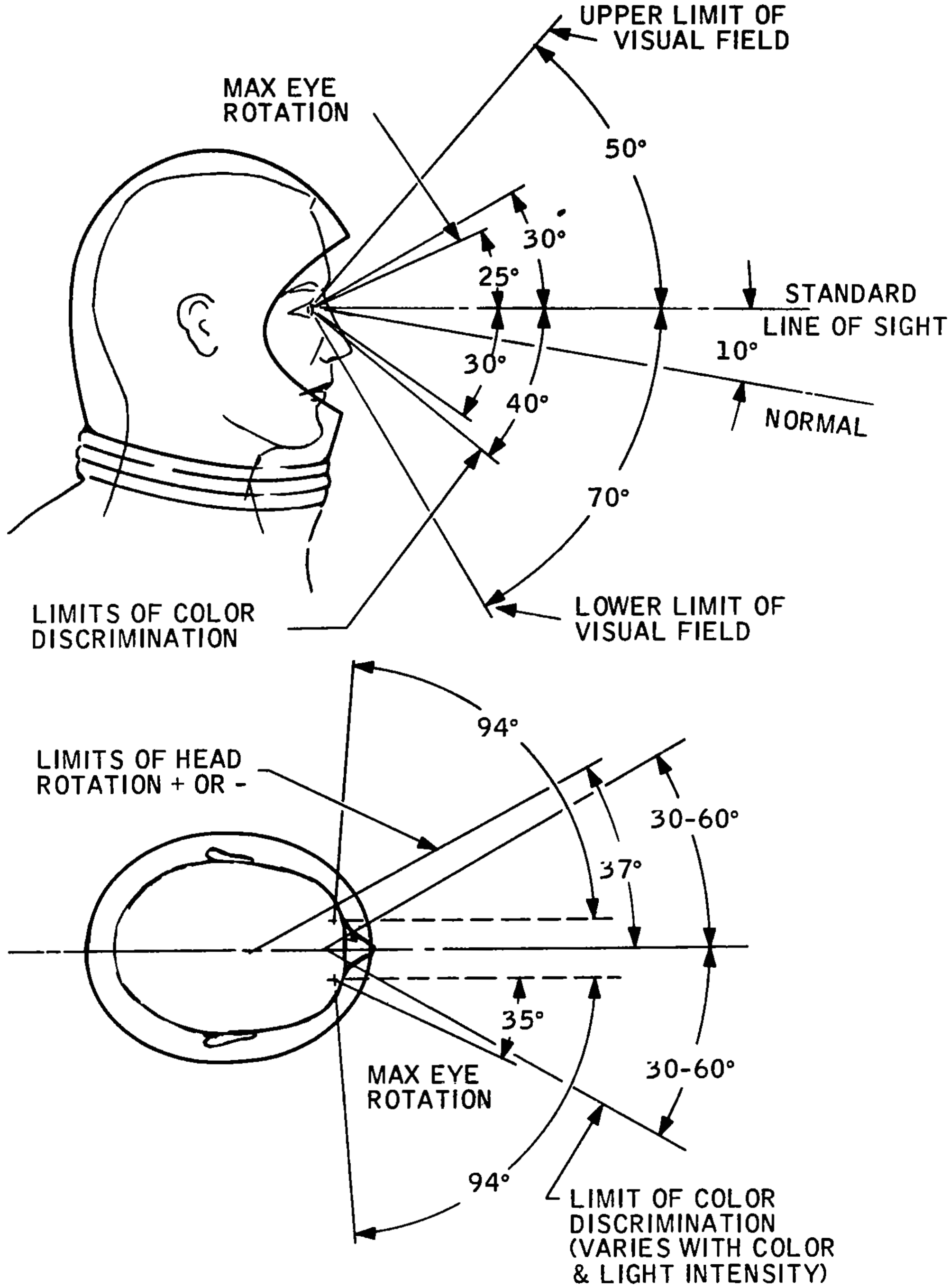


Figure I-2. Visual Limits

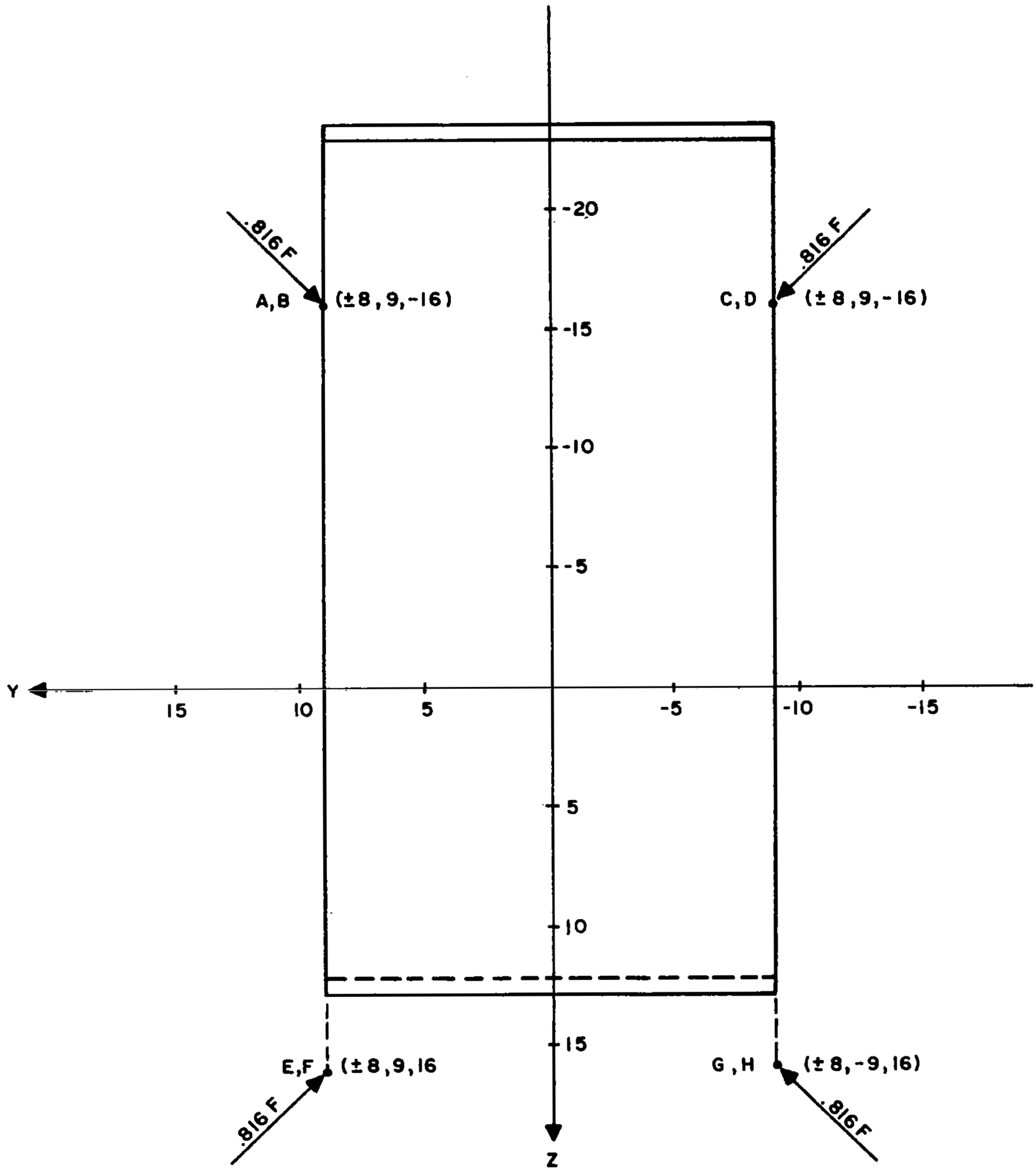


Figure I-3a. Principal Axes for Astronaut Position 1 and 190-lb Backpack (Front View)

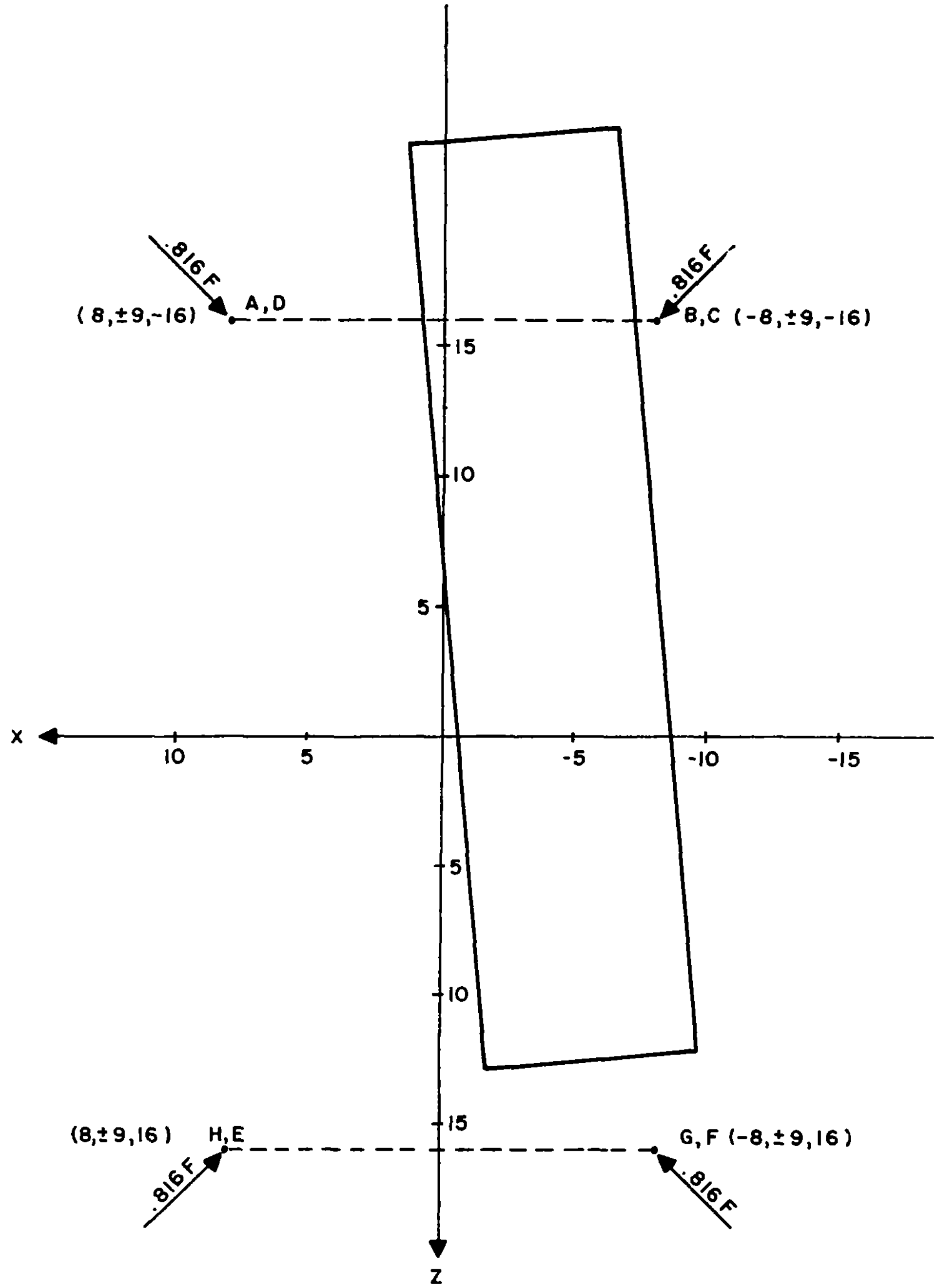


Figure I-3b. Principal Axes for Astronaut Position 1 and 190-lb Backpack (Side View)

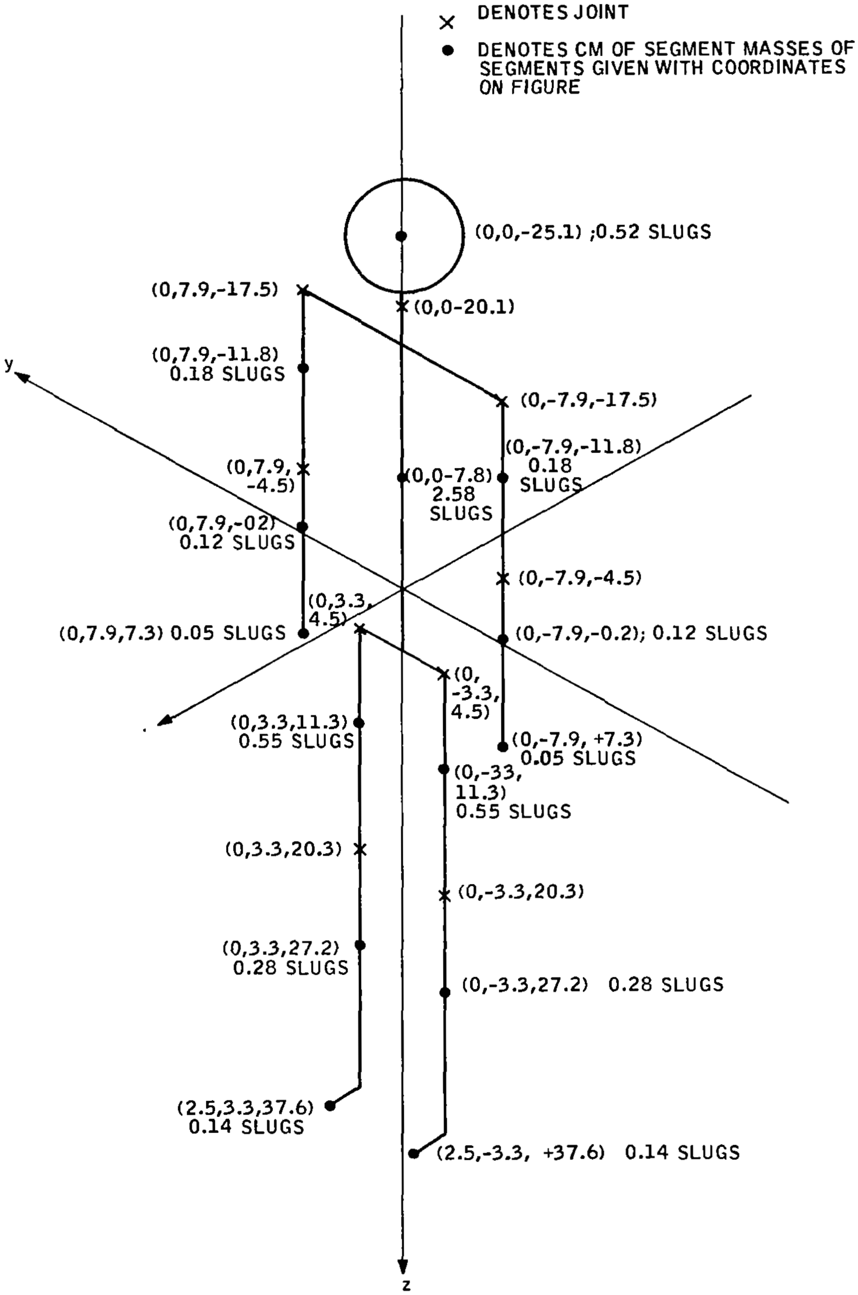


Figure I-4a. Position 1, Standing Erect - Arms at Sides

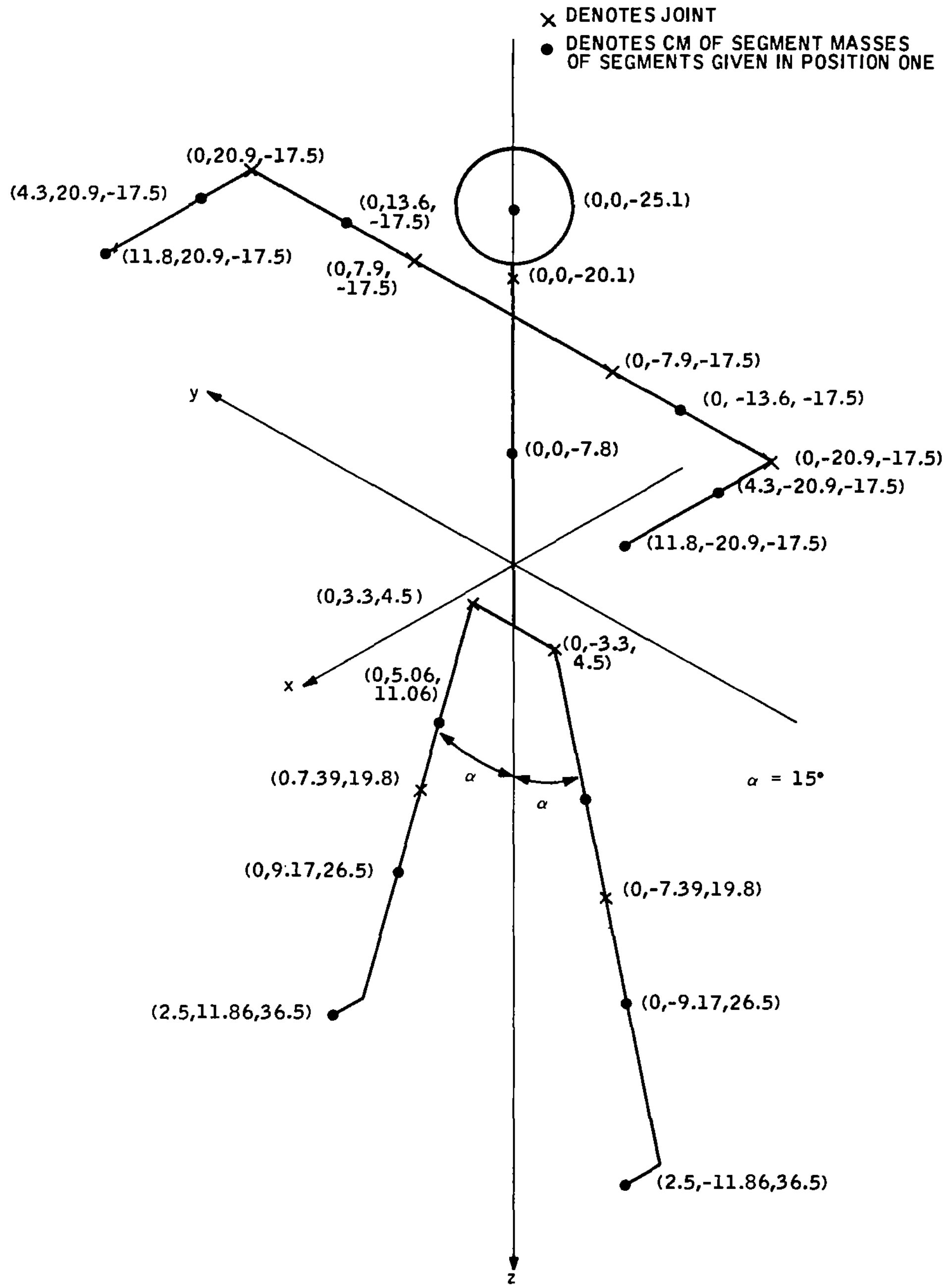


Figure I-4b. Position 2, Standing Erect - Legs Spread - Arms at Rest in Horizontal Plane

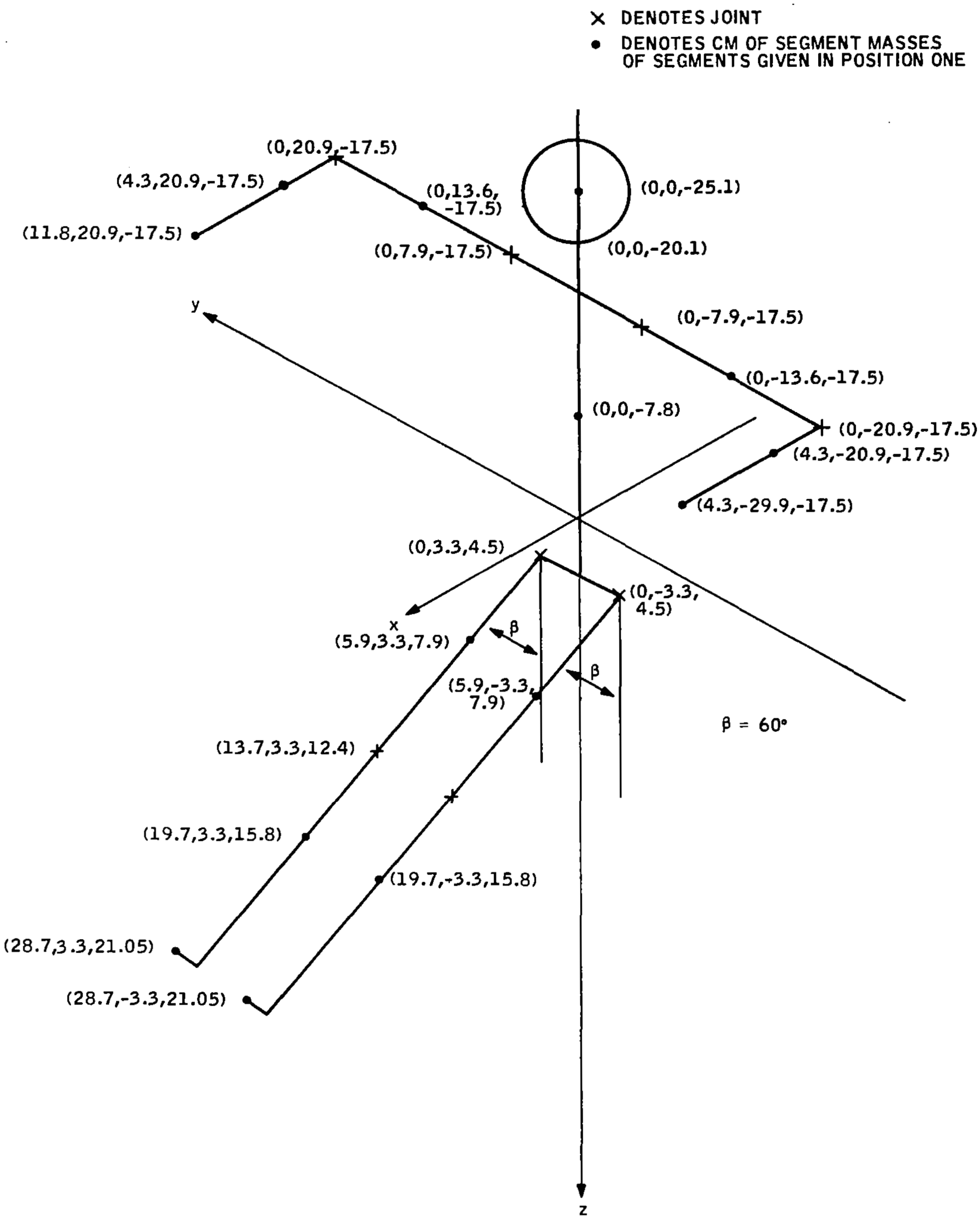


Figure I-4c. Position 3, Arms at Rest in Horizontal Plane - Legs Parallel But Deflected Forward

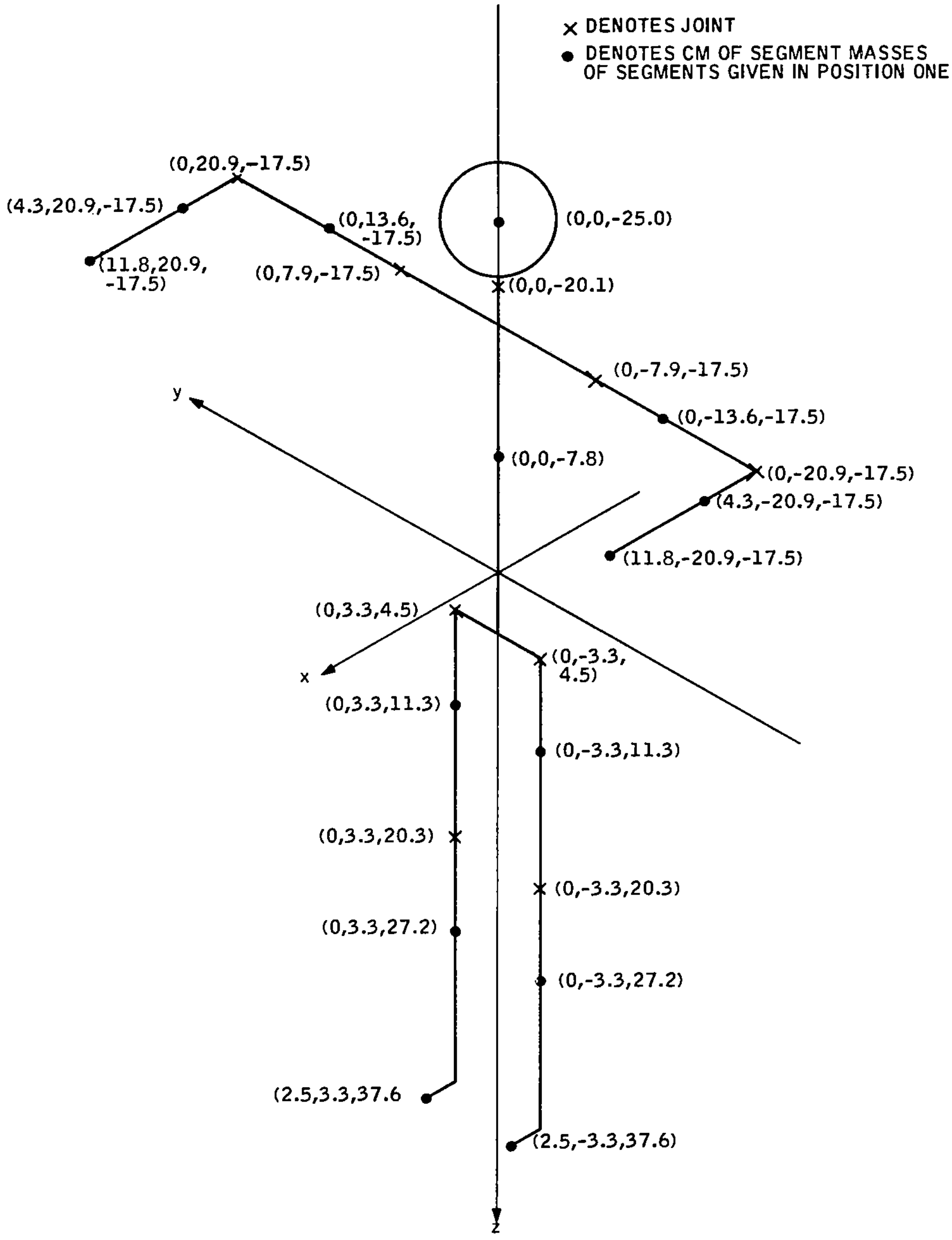


Figure I-4d. Position 4, Arms at Rest in Horizontal Plane - Legs Parallel and Vertical

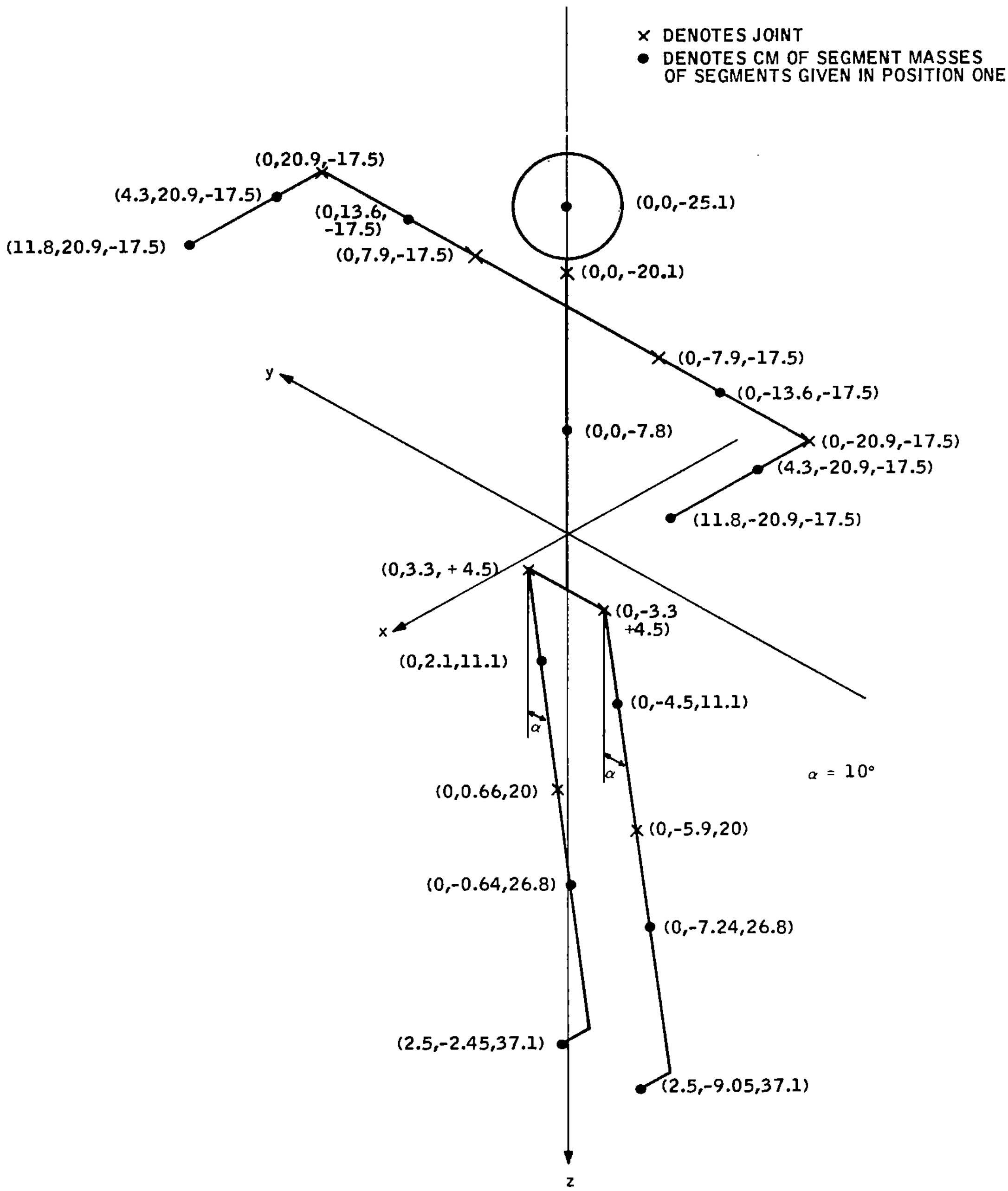


Figure I-4e. Position 5, Arms at Rest in Horizontal Plane - Legs Parallel and Deflected to One Side

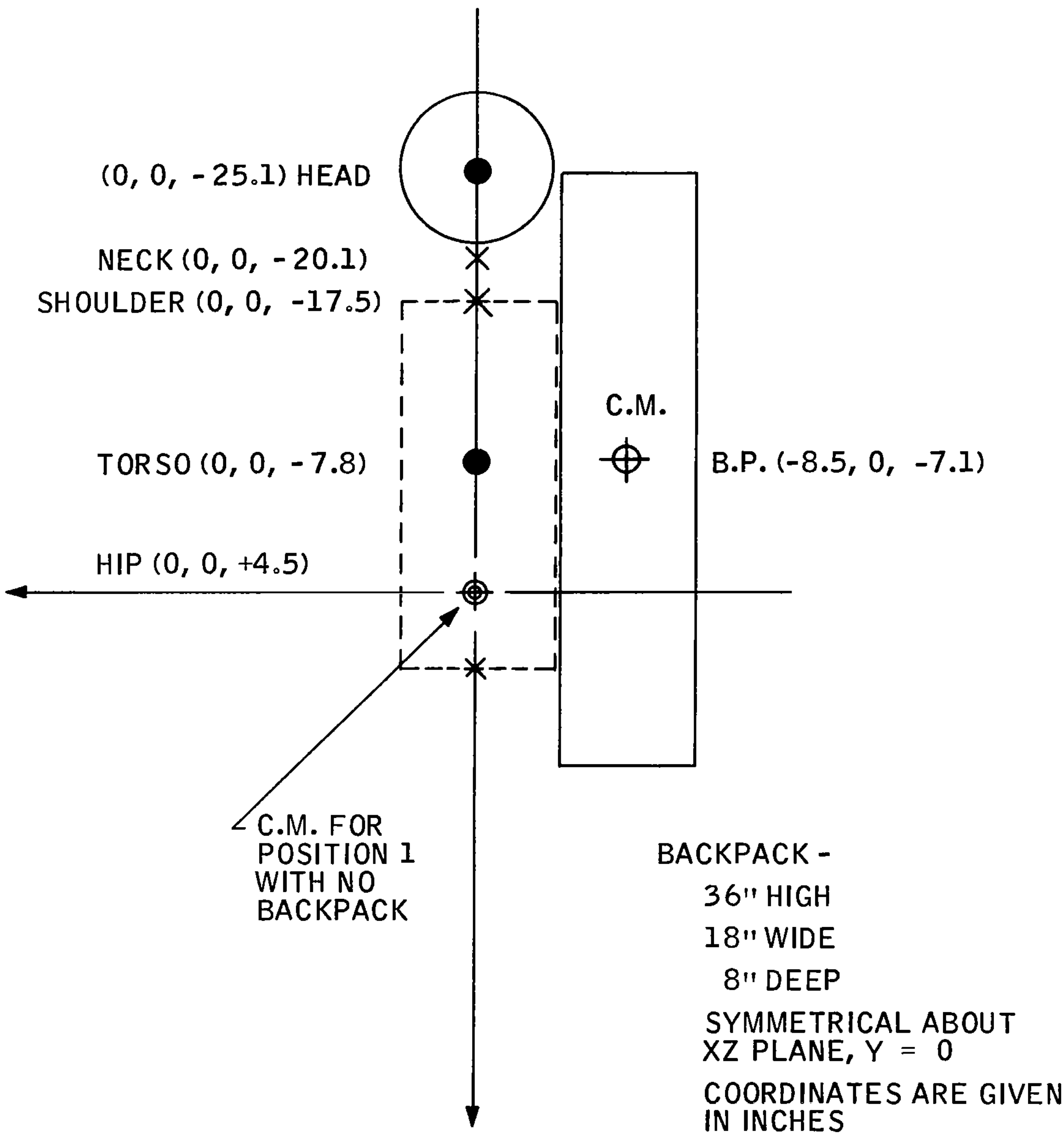


Figure I-5. Relative Locating of Astronaut and Backpack Centers of Mass

SECTION II

SPECIFICATIONS FOR THE ASTRONAUT MANEUVERING UNIT ATTITUDE CONTROL SYSTEM

Sensors and Control Electronics

1.0 SCOPE

1.1 This specification defines the design requirements for the sensors and control electronics of the attitude control system (ACS) for the astronaut maneuvering unit (AMU).

1.2 The sensors shall consist of three orthogonally mounted floated integrating gyros together with their mounting and attaching hardware and electrical connections.

1.3 The control electronics shall consist of circuits and components necessary to:

a. Provide all necessary voltages for the ACS except 28-vdc unregulated power which will be furnished from a battery in the AMU.

b. Develop attitude control signals in response to error signals from the sensors.

c. Operate reaction jets in response to inputs from the controller and attitude error circuits.

d. Torque the sensors in response to signals from the controller.

e. Provide drift compensation for the sensors if this is required to meet drift specifications.

2.0 APPLICABLE SPECIFICATIONS AND REFERENCES

2.1 NASA Contract NASw-841

2.2 Section I, "Requirements for the Astronaut Maneuvering Unit Attitude Control System", of **Appendix A** of 1781-FR1, 15 June 1964.

2.3 Test Conditions

2.3.1 Operation During Test

In those tests which call for equipment operation, the torquer amplifiers, gyros, power supplies, and switching amplifiers shall be operated according to the following scheme:

2.3.1.1 Simulated loads shall be connected to the jet drivers and power supplies. Simulated loads for the jet drivers are described in Paragraphs 5.2.3.1.5 and 5.2.3.2.8 of Section I of this volume. Simulated loads for power supplies shall draw rated current.

2.3.1.2 Simulated torque commands shall be supplied by external equipment.

2.3.1.3 Each gyro shall be torqued in one direction until the proper jet drivers are actuated. Then it shall be torqued in the opposite direction until the opposite jets fire and so on. Jet drivers shall operate according to the device specification.

2.3.2 Mechanical Vibration

2.3.2.1 Nonoperating -- The equipment shall be attached to the vibration machine by fasteners and attachment points intended for installation in the AMU. The equipment shall be subjected to random vibration at the input power density shown by Curve I of Figure II-1 by a load-equalized shaker for a period of

15 minutes along each of three mutually orthogonal axes. Clippers used to limit peak accelerations shall be not less than 3 sigma. Proper operation shall be established by functional tests according to the applicable device specification both before and after each 15-minute period. The equipment shall also be subjected to two sweeps of the vibration shown by Curve I of Figure II-2 along the same three mutually orthogonal axes as used for random vibration. Time to complete one sweep shall be 7 to 10 minutes. Again proper operation shall be established before and after each session.

2. 3. 2. 2 Operating -- The equipment shall be subjected to the random vibration of Paragraph 2. 3. 2. 1 except with the input power density shown by Curve II of Figure II-1 and to the nonrandom vibration of Paragraph 2. 3. 2. 1 except at the levels shown by Curve II of Figure II-2. During each vibration period, the torquer amplifiers, gyros, power supplies, and switching amplifiers shall be operated according to Paragraph 2. 3. 1.

2. 3. 3 Temperature

2. 3. 3. 1 High Temperature -- The equipment shall be exposed to a test chamber whose walls are maintained at 160°F. Mounting of the equipment shall minimize conduction to and from the walls. After reaching equilibrium, power shall be applied and functional tests shall be completed according to the applicable device specification.

2. 3. 3. 2 Low Temperature -- The equipment shall be exposed to a test chamber whose walls are maintained at -60°F. Mounting of the equipment shall minimize conduction to the walls. After reaching equilibrium, power shall be applied and all functional tests shall be completed according to the applicable device specification.

2.3.4 Radio Frequency Interference Tests

The equipment shall meet the requirements of MIL-I-6181D. During this test, the equipment shall be operated as described in Paragraph 2.3.1.

2.3.5 Acoustic Noise

The equipment shall perform within specification limits during and after exposure to the sound levels specified in Figure II-3. Duration of the test will be 30 minutes -- 10 minutes in each of three mutually orthogonal directions.

2.3.6 Acceleration

The equipment shall be subjected to the test of Procedure I of MIL-E-5272. The acceleration level shall be increased linearly with time from 1 g to 7.5 g's over 300 seconds and held at 7.5 g's for 60 seconds. The acceleration shall be applied along an axis corresponding to the longitudinal axis of the launch vehicle. The 90-degree rotation specified in Paragraph 4.16.1 of MIL-E-5272 shall not be performed. At completion of the test, proper operation of the equipment shall be verified by testing according to the applicable device specification.

2.3.7 Altitude

The equipment shall be mounted to a cold plate with the other five sides insulated. Ambient pressure shall be reduced below 1.5×10^{-5} psia. The equipment shall then be operated according to Paragraph 2.3.1. The cold plate shall be held at 70°F for one hour. At the end of this hour, the cold plate temperature shall be raised from 70°F to 100°F in 30 minutes, held at 100°F for 30 minutes; and then reduced from 100°F to 70°F in 30 minutes. The cold plate temperature shall then be held at 70°F for 90 minutes. The average heat input to the cold plate from the equipment shall not exceed 25 watts per square foot. At this time, the pressure shall be raised to room ambient and proper operation of the equipment established by testing according to the applicable device specification.

2.3.8 Salt Atmosphere

The equipment shall be subjected to Salt Fog Test Method 509 of MIL-STD-810. After 24 hours at room ambient conditions, the equipment shall perform within specification limits.

2.3.9 Sand and Dust

The equipment shall be subjected to Sand and Dust Procedure I of MIL-E-5272 for 50 hours. The equipment shall perform within specification limits at the end of this test.

2.3.10 Fungus

The equipment shall be subjected to Fungus Test Procedure I of MIL-E-5272 unless all materials used in fabrication are non-nutrients to fungi. At the completion of this test, the equipment shall perform within specification limits.

2.3.11 Humidity

The equipment shall be exposed to 100 percent relative humidity for 48 hours. The temperature shall be held between 65 and 85°F. At the end of this period, the external surfaces of the equipment (including external connectors) shall be wiped dry and then exposed to 65 to 85°F with relative humidity less than 80 percent for 24 hours. At the end of this period, the equipment shall perform within specified limits.

2.3.12 Shock

When subjected to 50-g shock along the axis designated by the device specification, the equipment shall not break loose from its mounts and all internal parts shall be contained within the equipment. The shock shall be applied as a sinusoidal pulse of 11 ms duration. The equipment need not operate after the test.

3.0 DESIGN REQUIREMENTS

3.1 Sensors

3.1.1 General Description

The gyro shall have a single degree of freedom with limited gimbal freedom. It shall be designated primarily for hard-mounted, strapped-down applications. The unit shall include a means of compensation for all gravity-insensitive torques. The operating temperature of the unit shall not exceed 200°F.

3.1.2 Passive Electrical Characteristics

The following nominal values are given as a guide or an indication of the expected mean.

3.1.2.1 Spinmotor Synchronous Impedance (at 400 cps): 75 + J130 ohms, line to neutral.

3.1.2.2 Signal Generator Impedance (at 400 cps):

Primary	49 + J17 ohms
Secondary	980 + J980 ohms

3. 1. 2. 3 Compensator Impedance (at 400 cps): 13 + J13 ohms

3. 1. 2. 4 Torque Generator:

Resistance	170 ohms
Inductance	5 millihenries

3. 1. 3 Mechanical and Dynamic Characteristics

3. 1. 3. 1 Weight: 1. 25 pounds maximum

3. 1. 3. 2 Dimensions: 4. 25 inches maximum length by 2. 25 inches maximum diameter

3. 1. 3. 3 Mounting and Alignment (flange mount with index notch):

Notch alignment error	3 mr maximum
Flange perpendicularity error	2 mr maximum

3. 1. 3. 3. 1 The gyro mounting structure shall provide a common heat sink between the gyros to minimize the number of temperature control components required.

3. 1. 3. 3. 2 Heat dissipation of electronic components will be used where possible as heat supply sources to the gyro mounting structure to minimize the temperature control operating power.

3. 1. 3. 3. 3 Heat transfer between the sensor package and the AMU structure will be controlled for minimum temperature control operating power.

3. 1. 3. 3. 4 Maximum power dissipation of the sensor package to the AMU mounting structure shall be 25 watts per square foot.

3.1.3.4 Drift and Maximum Rates of Temperature: The gyro shall have a maximum drift rate (gravity insensitive) of 1 deg/hr after having first been trimmed at normal operating temperature and after completing 3 warm-up cycles from a -30°F ambient condition.

3.1.3.5 Input Axis Freedom: The gyro shall have an input axis freedom of ±14 degrees minimum, ±20 degrees maximum.

3.1.3.6 An SN-20-20 PS Continental connector shall be used.

3.1.4 Performance Characteristics

3.1.4.1 Spinmotor: The spinmotor shall be a three-phase synchronous motor designed to operate at 26 v rms, 400-cps nominal line-to-line voltage and shall maintain synchronous speed down to 15 v rms, 400 cps line-to-line. The spinmotor should not draw more than 150 ma from each phase when in synch and running from a 3-phase, 26 v rms line-to-line voltage system.

3.1.4.2 Signal Generator: The primary excitation of the signal generator shall be 26 v rms, 400 cps. When excited from such a source and with the secondary loaded with 15 k ohms the primary shall draw no more than 55 ma rms from the 26 v rms source. The signal generator shall have a scale factor of 12.5 v rms per radian ±5 percent.

3.1.4.3 Torque Generator: The torque generator shall be of the permanent magnet type (which requires no excitation) and have a control parameter of 0.3 deg/sec/ma ±5 percent nominal, with a linearity of 0.2 percent for torque rate versus torquer current from 0 to ±100 ma, and a linearity of 1 percent for torque rate versus input angle between 0 and ±50 milliradians.

3.1.4.4 Transfer Function Linearity: The incremental slope of the gyro transfer function shall not deviate by more than 10 percent from the mean over the entire range of gimbal travel.

3.1.4.5 Phasing: Gyro axis and positive rotations are defined in Figure II-4. With the spinmotor turning in a positive direction, positive rotation of the gyro about the input axis shall cause positive rotation of the gimbal. Positive torque from the torque generator shall also cause positive rotation of the gimbal.

3.1.4.6 Spinmotor Rotation Detector: The gyro shall contain a spinmotor rotation detection device capable of supplying a 10-kilohm load with a minimum signal of 200 millivolts rms, 800 cps when the gyro spinmotor has reached synchronous speed.

3.1.4.7 Drift: The gyro shall after environmental exposure per Paragraph 2.3 exhibit no more than the following categorized drift rates:

Acceleration Insensitive	1 deg/hr maximum
Acceleration Sensitive	3 deg/hr/g
Acceleration^2 Sensitive	0.02 deg/hr/g^2 rms
Random Drift Rate	0.05 deg/hr
Elastic Restraint	1 deg/hr/deg IA to ± 3.5 deg IA 1.5 deg/hr/deg IA to ± 10 deg IA

3.1.4.8 Induced Voltage:

3.1.4.8.1 Sensing Element -- With standard excitation applied to the spinmotor, signal generator, and operating heater, the open circuit rms voltage induced in the temperature-sensing element shall not exceed 3.0 mv.

3.1.4.8.2 Motor and Heater Noise -- With the standard excitation applied to the spinmotor and operating heater and all circuitry removed from the signal generator, primary and torque generator, the voltage induced in the open circuit signal generator secondary shall not exceed 5 mv rms.

3.1.4.8.3 Signal Generator Null -- With the gyro at operating temperature and standard excitation applied to the spinmotor, signal generator primary, and operating heater, the null or minimum signal generator secondary voltage shall not exceed:

400 cps component (quadrature only)	2.0 mv rms
800 cps component	3.5 mv rms
2400 cps component	5.0 mv rms

3.2 Control Electronics

3.2.1 General

The electronics will consist of all logic and signal processing circuitry necessary to operate eight reaction jets.

3.2.2 Details

3.2.2.1 Interfaces

3.2.2.1.1 The electronics shall operate eight propulsion jets in response to controller commands and attitude errors. Design characteristics of the valves can be found in Paragraphs 5.2.3.1 and 5.2.3.2 of Section I of this volume.

3.2.2.1.2 The controller shall supply jet operating power to the electronics. The controller will also supply six translational command signals and 19 gyro torquing commands.

3.2.2.1.3 The AMU power system will supply unregulated 28-vdc battery power. Maximum power drain shall be 360 watts. This includes electronics, gyros, heaters, and six reaction jets.

3.2.2.1.4 The sensors will supply three attitude error signals to the control electronics. The control electronics will supply torquing power, spinmotor power and signal generator excitation to the sensors.

3.2.3 Electrical Design

The electronics may be divided into three sections for discussion of their functional requirements. These need not represent spatial, functional, or modular subdivisions of the actual device. The sections are torquer amplifiers, attitude error circuits, and thrust logic.

3.2.3.1 Torquer Amplifiers -- The input to the torquer amplifiers will be the torquer commands from the controller. The output of the torquer amplifiers will be voltages or currents of the proper sense and magnitude to the proper gyro.

3.2.3.2 Attitude Error Circuits -- The input to the attitude error circuits will be the output of the sensor signal generators. The output of the attitude error circuits will be six logic signals designated:

I - Positive yaw error
J - Negative yaw error
K - Positive pitch error
L - Negative pitch error
M - Positive roll error
N - Negative roll error

The Boolean notation used throughout will be:

1 represents the transmitting state (in particular when the logic variable representing a thrust jet is equal to 1, the jet is on)

0 represents the blocking state (jet off)

J' is the complement of J ("not J")

3.2.3.2.1 The pulse circuit portion of the attitude error circuits will behave in the following manner:

I, K, or M = 1 for 17 milliseconds whenever the appropriate attitude error reaches +12 mr

J, L, or N = 1 for 17 milliseconds whenever the appropriate attitude error reaches -12 mr

3.2.3.2.2 Each of three pseudo rate circuits will consist of two electronic logic switches and associated feedback circuitry. The description that follows uses the terminology of d-c switching circuits but is not intended to prejudice the circuit design. The block diagrams are intended to indicate function rather than circuit details. Instead of voltage levels, error magnitude will be specified in milliradians of input angular error.

When the respective input error reaches +17 mr with an initial feedback voltage of zero, the I, K, and M switches shall switch I, K, and M from 0 to 1. The I, K, and M switches will also apply a negative step delayed 5 ms to a feedback network with a transfer function of T/(S+T) where $T = 1\ \text{sec}^{-1}$.

When the respective input error reaches -17 mr with an initial feedback voltage of zero, the J, L, and N switches shall switch J, L, and N from 0 to 1. The J, L, and N switches shall at the same time apply a positive step input delayed 5 ms to the feedback network.

3.2.3.2.3 Upon a logic input from the controller the deadband limits of Paragraph 3.2.3.2.2 shall be switched from 17 mr to 160 mr.

3.2.3.3 Thrust Logic -- Power to operate the propellant valves shall be supplied to the control electronics from the controller. When this power is on, the jets shall operate according to the last set of Boolean equations in this paragraph.

Nomenclature:

$$\left.\begin{array}{l} A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \end{array}\right\} \text{Jets}$$

The location and line of action of these jets are shown in Section I, Figure I-3 of this volume.

O - +X (forward)	thrust command	Inputs to the thrust logic from the controller
P - -X (aft)	thrust command	
Q - +Y (right)	thrust command	
R - -Y (left)	thrust command	
S - +Z (down)	thrust command	
T - -Z (up)	thrust command	

$$\begin{aligned}
A &= (P+R+S)\, I'K'N' + (J+L+M)\, O'Q'T' \\
B &= (O+R+S)\, J'L'N + (I+K+M)\, P'Q'T' \\
C &= (O+Q+S)\, I'L'M' + (J+K+N)\, P'R'T' \\
D &= (P+Q+S)\, J'K'M' + (I+L+N)\, O'R'T' \\
E &= (P+R+T)\, I'L'M' + (J+K+N)\, O'Q'S' \\
F &= (O+R+T)\, J'K'M' + (I+L+N)\, P'Q'S' \\
G &= (O+Q+T)\, I'K'N' + (J+L+M)\, P'R'S' \\
H &= (P+Q+T)\, J'L'N' + (I+K+M)\, O'R'S'
\end{aligned}$$

Insofar as possible, the failure modes with the highest probability shall fail in such a way as to make jet actuation less likely.

3.2.4 Mechanical Design

The control electronics shall weigh less than 3 pounds and occupy no more volume than 85 cubic inches. Modular construction shall be employed where practicable.

3.2.5 Reliability

The reliability goal for the control electronics is 0.9987 for a four-hour mission. Reliability is defined as the probability the control electronics will perform the functions described in Paragraph 3.2.3.

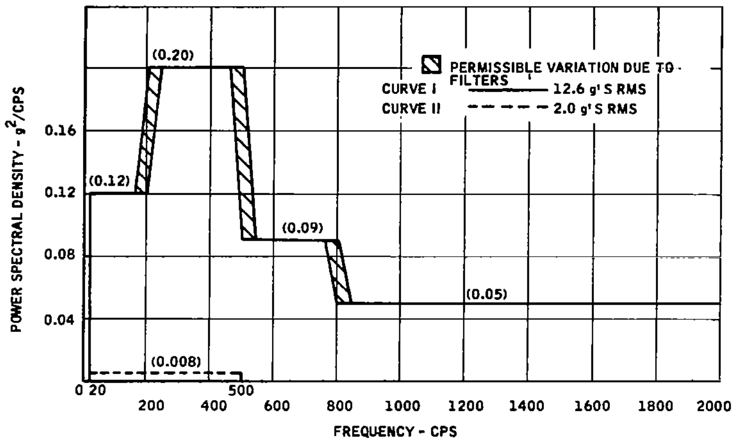


Figure II-1. Input Power Density for Random Vibration Test

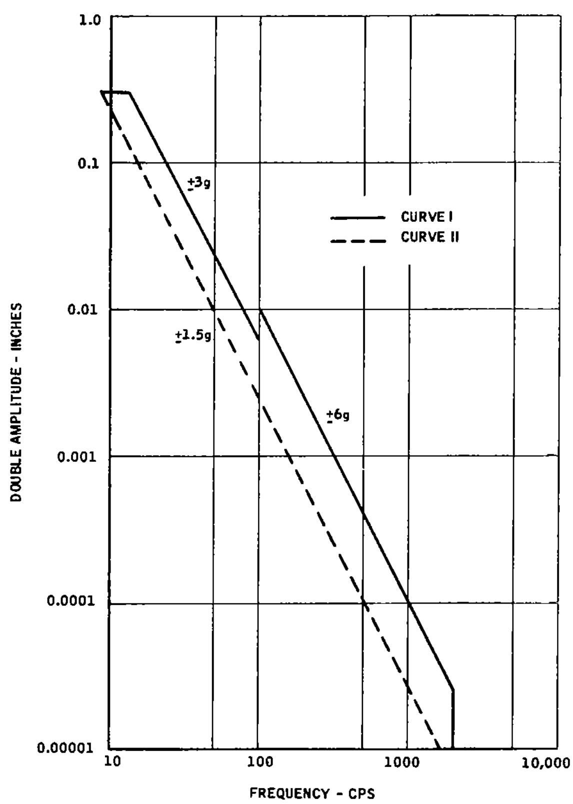


Figure II-2. Acceleration Level for Vibration Test

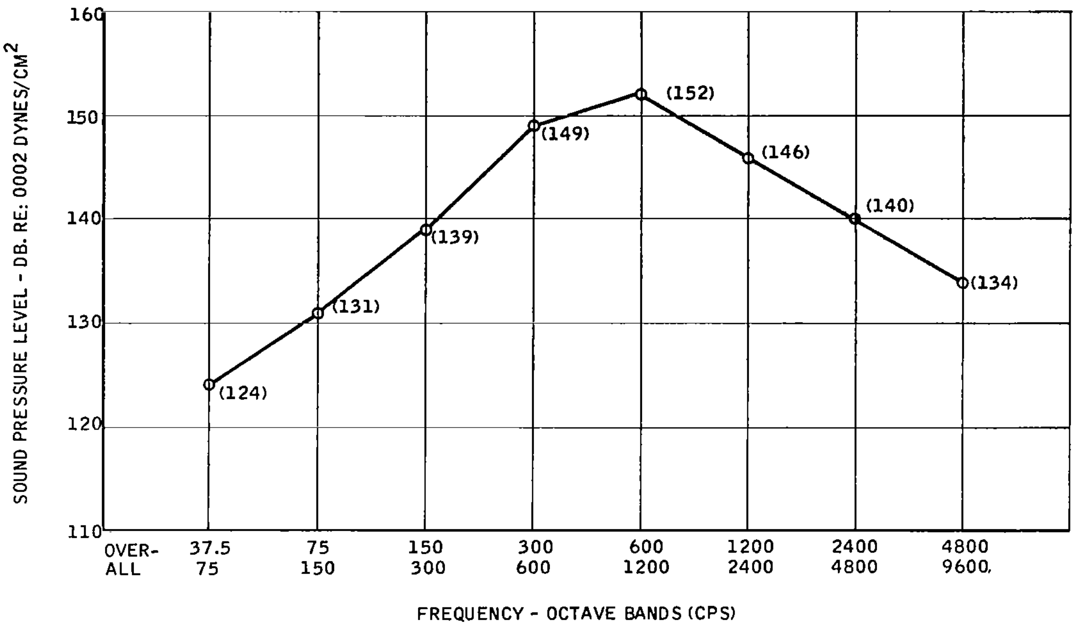


Figure II-3. Acoustic Noise Level for Acoustic Noise Test

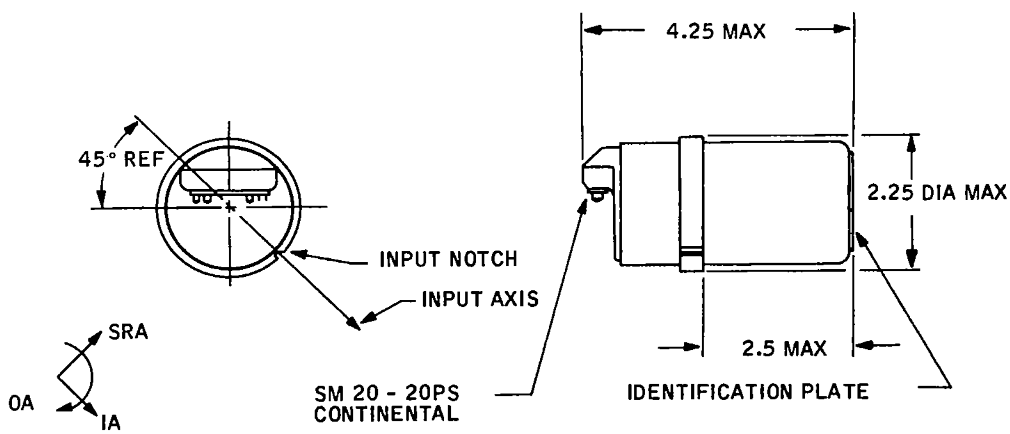


Figure II-4. Gyro Axes

SECTION III

PERFORMANCE SPECIFICATION FOR THE ASTRONAUT MANEUVERING UNIT ATTITUDE CONTROL SYSTEM CONTROL ELECTRONICS

1.0 SCOPE

This specification defines performance requirements for the control electronics of the attitude control system (ACS).

1.1 The control electronics shall consist of circuits and components necessary to:

a. Develop attitude control signals in response to sensor error signals.

b. Operate reaction jets in response to sensor error signals and commands from the controller.

c. Torque sensors in response to controller command signals.

d. Control sensor thermal environment.

e. Provide sensor drift compensation.

f. Provide necessary voltages for sensor and electronics functioning from the unregulated 28 vdc AMU battery.

1.2 Electrical Design

1.2.1 Functional Requirements

The ACS control electronics is vided physically and functionally into the following parts:

a. Control Logic and Temperature Control Amplifier: Honeywell Drawing No. SK92529*

b. ACS Axis Computers and Sensor Torquer Amplifiers:

Pitch Axis: Honeywell Drawing No. SK92531

Roll Axis: Honeywell Drawing No. SK92532

Yaw Axis: Honeywell Drawing No. SK92533

c. Reaction Jet Drivers: Honeywell Drawing No. SK92530

d. Power Supply: Honeywell Drawing No. SK92534

1.2.1.1 Control Logic and Temperature Control Amplifier (SK92529)

1.2.1.1.1 The control logic shall accept digital inputs of the form "1" = +6 vdc and "0" = 0 vdc from the controller and the ACS axis computers. The control logic shall perform the logic functions described in the following Boolean equations:

$$A = (P+R+S)\, I'K'N' + (J+K+M)\, O'Q'T'$$
$$B = (O+R+S)\, J'L'N' + (I+K+M)\, P'Q'T'$$
$$C = (O+Q+S)\, I'L'M' + (J+K+N)\, P'R'T'$$
$$D = (P+Q+S)\, J'K'M' + (I+L+N)\, O'R'T'$$
$$E = (P+R+T)\, I'L'M' + (J+K+N)\, O'Q'S'$$
$$F = (O+R+T)\, J'K'M' + (I+L+N)\, P'Q'S'$$
$$G = (O+Q+T)\, I'K'N' + (J+L+M)\, P'R'S'$$
$$H = (P+Q+T)\, J'L'N' + (I+K+M)\, O'R'S'$$

*Honeywell drawings referred to in this volume are contained in Appendix B of this final report.

Where A, B, C, D, E, F, G, and H represent the reaction jets:

I - positive yaw error	J - negative yaw error
K - positive pitch error	L - negative pitch error
M - positive roll error	N - negative roll error
O - +x thrust command	P - -x thrust command
Q - +y thrust command	R - -y thrust command
S - +z thrust command	T - -z thrust command

B′, for example, denotes the complement of B - "not B"

1.2.1.1.2 The temperature control amplifier shall continuously monitor the sensor package temperature. During normal operation it shall maintain the gyros at their nominal operating temperature (+180°F). The temperature control amplifier shall continuously apply heater power during warm-up, until the sensor package temperature reaches nominal operating temperature (+180°F).

1.2.1.2 Attitude Control System Axis Computers and Sensor Torque Amplifiers

1.2.1.2.1 Attitude Control System Axis Computers

1.2.1.2.1.1 Synchronous Mode: The control electronics shall prevent reaction jet firing due to computer action and shall maintain the sensors within 1 degree of null attitude for all input attitude rates less than 20 deg/sec. This is the normal mode of the ACS; that is, no input signal shall be required to establish this mode other than the application of primary electrical power. No controller command inputs shall be allowed during this mode.

1.2.1.2.1.2 Normal Limit Operate Mode: The control computer shall provide attitude stabilization within the specified limits of Section I of this volume for the various program profile work tasks. The control computer, upon controller command, shall produce translational thrust along the axes of the unit in both senses. The control computer shall produce three levels of rotational rate in both senses about each axis in response to controller command. Each rotational rate, in each sense about each axis, is in response to a unique and distinct controller command input to the ACS. The translational thrust and rotational rates shall persist for the duration of the controller command input to the ACS.

1.2.1.2.1.3 Extended Limit Operate Mode: In response to a controller command, the ACS control computer shall expand the attitude limit cycle deadband. Responses to translational and rotational controller commands shall remain unchanged; however, rotational command responses may appear different due to the wide deadband.

1.2.1.2.1.4 Emergency Mode: Solenoid 28 vdc power and the operate signal shall be removed from the ACS computers. Removal of these voltages shall prevent reaction jet firing and shall place the ACS in synchronous mode.

1.2.1.2.2 Sensor Torque Amplifiers

The sensor torquer amplifiers are required to torque the sensors in response to digital inputs from the controller.

1.2.1.3 Reaction Jet Drivers (SK92530)

The reaction jet drivers are required to switch the operating current of the reaction jet solenoid valves in response to the outputs of the command logic.

1.2.1.4 Power Supply (SK92534)

The power supply is required to furnish all power for the operation of the sensor and control electronics except unregulated 28 vdc.

2.0 APPLICABLE SPECIFICATIONS AND REFERENCES

2.1 Section I, "Requirements for the Astronaut Maneuvering Unit Attitude Control System," of **Appendix A**

2.2 Section II, "Specifications for the Astronaut Maneuvering Unit Attitude Control System Sensors and Control Electronics," of **Appendix A)** of 1781-FR1, 15 June 1964

2.3 Diagrams (see **Appendix B**)

SK92529	SK92532
SK92530	SK92533
SK92531	SK92534

3.0 DETAIL COMPONENT REQUIREMENTS

3.1 Control Logic and Temperature Control Amplifier (SK92529)

3.1.1 Control Logic

3.1.1.1 Input Characteristics

3.1.1.1.1 Power -- The input to pin 8 of SK92529 shall be +6 ± 0.1 vdc at 55 ma maximum current with a maximum ripple of 0.2 v rms and maximum source impedance of 3 ohms.

3.1.1.1.2 Signal -- The input signals to pins I, J, K, L, M, N, O, P, Q, R, S, and T of SK92529, shall be of the digital form "1" equals +6 ± 0.6 vdc with a maximum source impedance of 4.5 kilohms. "0" equals 0 ± 0.6 vdc from a 4.5 kilohm source impedance.

3.1.1.1.3 Noise -- The input signal noise content shall have an E^2t product less than 0.5×10^{-6} v^2 seconds for frequencies above 800 cps, where v is the peak amplitude of the noise voltage and t is the pulse duration or $1/4\pi f$. The input signal shall contain not more than 0.2 v rms each of 400- and 800-cps ripple.

3.1.1.2 Output Characteristics

3.1.1.2.1 Power -- The output shall display a maximum source impedance of 4.5 kilohms.

3.1.1.2.2 Signal -- The output of this device shall be +6 ± 0.6 vdc for "0" and 0 ± 0.6 vdc for "1".

3.1.1.2.3 Noise -- The noise contained in the output of this unit shall be 0.3 v peak and of less than 10 microseconds pulse duration, and shall contain not more than 0.2 v rms each of 400- and 800-cps ripple.

3.1.1.3 Functional Requirements: The unit shall accept inputs of the form specified in Paragraph 3.1.1.1 and provide outputs per 3.1.1.2 according to the following rules expressed as digital logic equations:

$$A = (P+R+S)\ I'K'N' + (J+L+M)\ O'Q'T'$$
$$B = (O+R+S)\ J'L'N' + (I+K+M)\ P'Q'T'$$
$$C = (O+Q+S)\ I'L'M' + (J+K+N)\ P'R'T'$$
$$D = (P+Q+S)\ J'K'M' + (I+L+N)\ O'R'T'$$
$$E = (P+R+T)\ I'L'M' + (J+K+N)\ O'Q'S'$$
$$F = (O+R+T)\ J'K'M' + (I+L+N)\ P'Q'S'$$
$$G = (O+Q+T)\ I'K'N' + (J+L+M)\ P'R'S'$$
$$H = (P+Q+T)\ J'L'N' + (I+K+M)\ O'R'S'$$

where

A, B, C, D, E, F, G, H	to jet drivers	The location and line of action of these jets are shown in Figure I-3, Section I of this volume.

I - Positive yaw error

J - Negative yaw error

K - Positive pitch error

L - Negative pitch error

M - Positive roll error

N - Negative roll error

O - +X (forward)	thrust command	Inputs to the thrust logic from the controller
P - -X (aft)	thrust command	
Q - +Y (right)	thrust command	
R - -Y (left)	thrust command	
S - +Z (down	thrust command	
T - -Z (up)	thrust command	

3.1.2 Temperature Control Amplifier

3.1.2.1 Input Characteristics

3.1.2.1.1 Power --

3.1.2.1.1.1 Pin 1 of SK92529: +12 ± 0.2 vdc at 12.5 ma from a 3-ohm (max) source containing less than 0.2 v rms each of 400 and 800 cps.

3.1.2.1.1.2 Pin 4 of SK92529: -12 ± 0.2 vdc at 18 ma from a 3-ohm (max) source containing less than 0.2 v rms each of 400 and 800 cps.

3.1.2.1.1.3 Pin 8 of SK92529: +6 ± 0.1 vdc at 5 ma from a 3-ohm (max) source containing less than 0.1 v rms each of 400 and 800 cps.

3.1.2.1.1.4 Pin 5 of SK92529: 28 ± 4 vdc at 24 ma from a source impedance of less than 5 ohms. Voltage source excursions below 24 vdc shall be limited to 15×10^{-6} seconds.

3.1.2.1.1.5 Pins 2 and 3 of SK92529: +6 v ground, +12 v ground, -12 v ground, and +28 v ground shall be tied together.

3.1.2.1.2 Signal -- This unit requires a temperature-sensitive resistor which is 780 ohms at +180°F and changes 1.5 ohms per degree F. This sensor element connects to a bridge to provide the needed temperature control error signal.

3.1.2.1.3 Noise -- The sense element shall have less than 750 millivolts rms each of 400 and 800 cps.

3.1.2.2 Output Characteristics

The maximum base drive to the sensor package heater element driver transistor from the temperature control amplifier shall be at least 18 ma. The noise in this signal shall be essentially that in the 28-vdc primary power source. With a 1.3-ohm resistor connected between pins 1 and 2 of SK92529 and less than 770 ohms between pins 6 and 9, a minimum of 18 ma current shall flow through the 1.3-ohm resistor; when the resistance between pins 1 and 2 is greater than 790 ohms, less than 10×10^{-6} amperes shall flow through the 1.3-ohm resistor.

3.2 Attitude Control System Axis Computer and Sensor Torquer

3.2.1 Attitude Control System Axis Computers

The following requirements pertain to the pitch (SK92532), roll (SK92531), and yaw (SK92533) ACS axis computers.

3.2.1.1 Input Characteristics

3.2.1.1.1 Power --

3.2.1.1.1.1 Pin 3: +12 ± 0.5 vdc at 8.5 ma maximum from a 3-ohm (maximum) source impedance containing less than 0.2 v rms each of 400 and 800 cps.

3.2.1.1.1.2 Pin 1: -12 ± 0.5 vdc at 21 ma maximum from a 3-ohm (maximum) source impedance containing less than 0.2 v rms each of 400 and 800 cps.

3.2.1.1.1.3 Pin 23: +6 ± 0.25 vdc at 27 ma maximum from a 3-ohm (max) source impedance containing less than 0.1 v rms each of 400 and 800 cps.

3.2.1.1.1.4 Pin 2: -6 ± 0.25 v rms 400 cps square wave at 1 ma maximum from a 0.15-ohm (max) source impedance. The square wave shall have a rise and fall time of less than 100 microseconds.

3.2.1.1.2 Signal --

3.2.1.1.2.1 Analog Attitude Signal: The input shall be a 400-cps square wave with a rise and fall time of less than 100 microseconds. The input waveform shall be in or out of phase with the waveform on pin 2. The input shall be applied between pins 20 and 21. An in-phase waveform shall denote pin 20 in phase with pin 2. The input signal shall be applied from a source of 1.4 kilohms or less impedance.

3.2.1.1.2.2 Digital Control Signals:

Operate Signal: +6 ± 0.25 vdc at 0.1 ma maximum at pin 4

Standby Signal: 0 ± 0.25 vdc at 0.001 ma maximum at pin 4

Range or Deadband Control:
17 mr: 0 ± 0.25 vdc at 0.001 ma at pin 22
160 mr: +6 ± 0.25 vdc at 10 ma at pin 22

3.2.1.2 Output Characteristics

3.2.1.2.1 Power -- The output of this unit shall be either 0 ± 0.5 vdc or +6 ± 0.5 vdc from a 4.5 kilohm source impedance.

3.2.1.2.2 Signal --

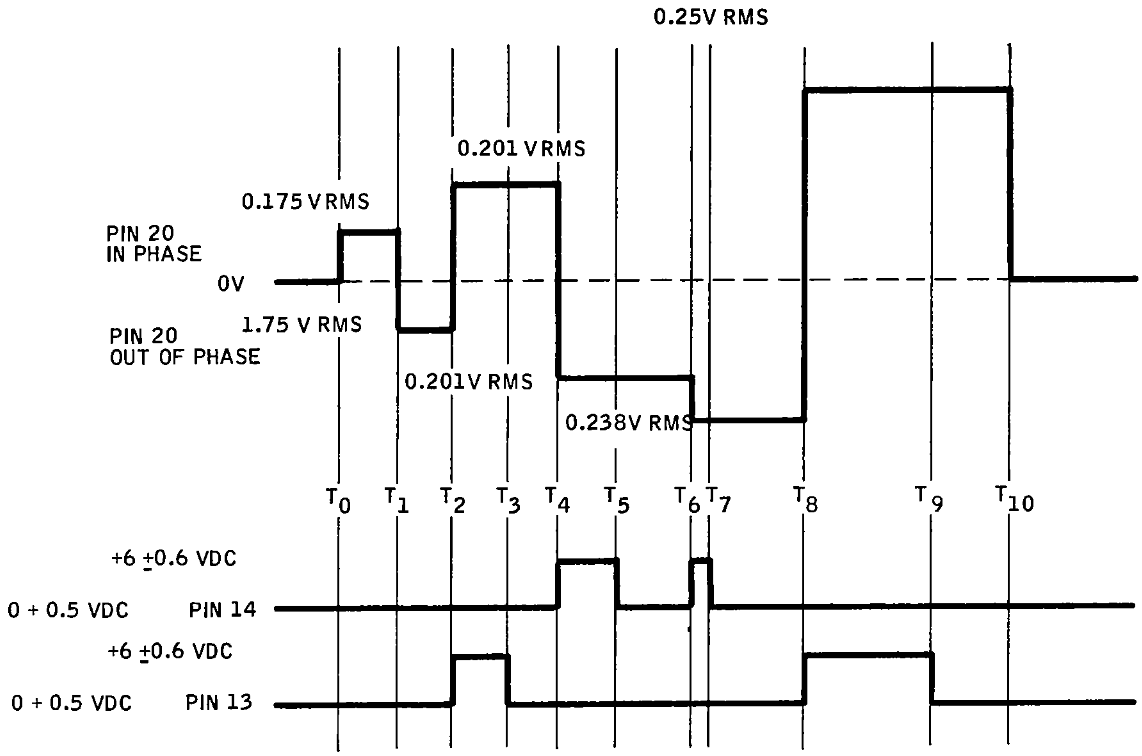
3.2.1.2.2.1 Normal Limit Operate Mode: The output between pins 13 and 14 shall show the relationship indicated in Figure III-1 with the input between pins 20 and 21, with +6 vdc applied to pin 4 and 0 vdc applied to pin 22.

3.2.1.2.2.2 Extended Limit Operate Mode: Apply +6 vdc to pin 22. The input levels of the preceding diagram shall be increased by the factor 8.9 to produce the same input pattern of output voltages and switching times.

3.2.1.2.2.3 Standby Mode: This mode is described in Paragraph 3.2.2.

3.2.2 Sensor Torquers

The following requirements pertain to the pitch (SK92532), roll (SK92531), and yaw (SK92533) axis sensor torquers.



$T_3 - T_2 = 17 \pm 1.7 \times 10^{-3}$ SECONDS

& $T_5 - T_4 = 17 \pm 1.7 \times 10^{-3}$ SECONDS

& $T_7 - T_6 = 5 \pm 1 \times 10^{-3}$ SECONDS

& $T_9 - T_8 = 37.7 \pm 4 \times 10^{-3}$ SECONDS

Figure III-1. Input-Output Relationships for Axis Computers

3.2.2.1 Input Characteristics

3.2.2.1.1 Power --

3.2.2.1.1.1 Pin 11: +20 ± 1 vdc at 100 ma maximum from a maximum source impedance of 3 ohms containing less than 0.3 v rms each of 400 and 800 cps.

3.2.2.1.1.2 Pin 9: -20 ± 1 vdc at 100 ma maximum from a max source impedance of 3 ohms containing less than 0.3 v rms each of 400 and 800 cps.

3.2.2.1.1.3 Pin 23: +6 ± 0.25 vdc at 2.5 ma maximum from 3 ohms maximum source impedance containing less than 0.1 v rms each of 400 and 800 cps.

3.2.2.1.1.4 Pin 3: +12 ± 0.5 vdc at 0.5 ma from a maximum source impedance of 3 ohms containing less than 0.2 v rms each of 400 and 800 cps.

3.2.2.1.1.5 Pin 1: -12 ± 0.5 vdc at 3.5 ma from a maximum source impedance of 3 ohms containing less than 0.2 v rms each of 400 and 800 cps.

3.2.2.1.2 Signal --

3.2.2.1.2.1 Standby Mode (gyro synchronization): 0 ± 0.1 vdc at pin 4

3.2.2.1.2.2 Operate Mode: +6 ± 0.1 vdc at pin 4

3.2.2.1.2.3 Rotational Rate Commands

Output	Input (vdc) and Pin No.					
Attitude Rate (deg/sec)	7	8	17	6	5	18
0	0	0	0	0	0	0
+20	+6	0	0	0	0	0
-20	0	0	0	+6	0	0
+ 3	0	+6	0	0	0	0
- 3	0	0	0	0	+6	0
+ 0.15	0	0	+6	0	0	0
- 0.15	0	0	0	0	0	+6

3.2.2.1.3 Noise -- Noise levels are not to exceed 0.1 v rms each at 400 and and 800 cps.

3.2.2.2 Output Characteristics

With a 170-ohm load connected between pins 12 and 16 of SK92531 the input-output characteristics shall be as follows:

Input (vdc) and Pin No.						Output*
7	8	17	6	5	18	Load Current (ma), Pins 12 to 16
+6	0	0	0	0	0	+90
0	+6	0	0	0	0	+13.5
0	0	+6	0	0	0	+ 0.676
0	0	0	+6	0	0	-90
0	0	0	0	+6	0	-13.5
0	0	0	0	0	+6	- 0.676
0	0	0	0	0	0	0

*Signs refer to the polarity of pin 12.
Current tolerance is ±10 percent

3.3 Reaction Jet Drivers (SK92530)

3.3.1 Input Characteristics

3.3.1.1 Power --

3.3.1.1.1 $+28 \pm 4$ vdc at 360 ma maximum from a source impedance of less than 3 ohms.

3.3.1.1.2 $+12 \pm 0.5$ vdc at 6.4 ma maximum from a source impedance of less than 3 ohms containing less than 0.2 v rms each of 400 and 800 cps.

3.3.1.1.3 -12 ± 0.5 vdc at 0.64 ma maximum from a source impedance of less than 3 ohms containing less than 0.2 v rms each of 400 and 800 cps.

3.3.1.2 Signal -- The input signal for each input point shall be either 0 ± 0.5 vdc or $+6 \pm 0.5$ vdc from a source impedance of less than 3 ohms containing less than 0.1 v rms each of 400 and 800 cps.

3.3.2 Output Characteristics

The output points shall be loaded with 2.6 ohms to ground. With all input points at 0 ± 0.5 vdc, all output points shall be 0 ± 0.01 vdc. When any input is raised to $+6 \pm 0.5$ vdc the corresponding output shall become $+0.11$ vdc ± 0.01 v. Input points are denoted on SK92530 by the letters A through H, and corresponding output points are denoted by the same letters followed by the subscript D.

3. 4 Power Supply

3. 4. 1 Input Characteristics

Input shall be +28 ± 4 vdc at 2 amperes maximum from a source impedance of less than 0. 1 ohms. Voltage source excursions below 24 vdc shall be limited to 15×10^{-6} seconds. Voltage excursions above 32 vdc shall be limited to 40 vdc maximum amplitude and 0. 1 second maximum duration at a maximum pulse recurrent frequency of 0. 1 cps.

3. 4. 2 Output Characteristics

The circuit of SK92534 must be properly connected to the reference transformer and the power transformer per SK92539 in order to evaluate its operation. When properly connected, and with primary power of 3. 4. 1 applied to pin 7, the power supply shall have the following output capabilities:

3. 4. 2. 1 Pin 6: +6 ± 0. 5 vdc at 150 ma maximum with a source impedance of 3 ohms maximum containing less than 0. 1 v rms each of 400 and 800 cps.

3. 4. 2. 2 Pin 20: +12 ± 0. 2 vdc at 30 ma maximum with a source impedance of 3 ohms maximum containing less than 0. 2 v rms each of 400 and 800 cps.

3. 4. 2. 3 Pin 17: -12 ± 0. 4 vdc at 100 ma maximum with a maximum source impedance of 3 ohms containing less than 0. 2 v rms each of 400 and 800 cps.

3. 4. 2. 4 Pin 24: +20 ± 1 vdc at 300 ma maximum from a maximum source impedance of 3 ohms and containing less than 0. 3 v rms each of 400 and 800 cps.

3. 4. 2. 5 Pin 22: -20 ± 1 vdc at 300 ma maximum from a maximum source impedance of 3 ohms and containing less than 0. 3 v rms each of 400 and 800 cps.

3.4.2.6 $+6 \pm 0.1$ v rms at 1.2 va both in and out of phase of a 400 cps ± 5 percent square wave having a maximum rise and fall time of 100 microseconds.

3.4.2.7 $+28 \pm 0.5$ v rms at 12 va of a 400 cps ± 5 percent square wave having a maximum rise and fall time of 100 microseconds

4.0 DETAIL ACS ELECTRONICS PACKAGE REQUIREMENTS

All pin numbers in the following discussion refer to those shown on SK92539.

4.1 Load Simulation

4.1.1 Jet Solenoid -- Connect 28-ohm, 50-watt resistors between J1 pins 41, 42, 43, 44, 45, 46, 47, and 48 and the +28 vdc supply.

4.1.2 Gyro Torquer -- Connect 170-ohm, 2-watt resistors between J2 pins 17 and 18, 26 and 27, and 33 and 34.

4.1.3 Temperature Sensor -- Connect a 1000-ohm potentiometer between J2 pins 29 and 30.

4.1.4 Sensor Heater -- Connect a 2.6-ohm, 5-watt resistor between J2 pins 8 and 9.

4.1.5 Sensor Signal Generator -- Connect a 40-ohm, 1-watt resistor between J2 pins 14 and 15.

4.1.6 Sensor Spinmotor -- Connect an 87-ohm, 10-watt resistor in series with a 21-millihenry choke between J2 pins 11 and 12.

4.2 Signal Source Simulation

Connect 1 kilohm, 0.5-watt resistors between J2 pins 4 and 5, 23 and 24, and 36 and 37; and connect J2 pins 5, 24, and 37 to J1 pin 2.

4.3 Standby Mode Operation

4.3.1 Apply +28 vdc to J1 pin 1 and 28 v ground to J1 pin 2. Then:

+28 vdc shall appear at J3 pin 1

28 ± 2 v rms 400 ± 10 cps shall appear at J3 pin 4

6 v rms ±10 percent 400 ± 10 cps shall appear at J3 pins 6 and 7 (The waveform at pin 7 shall be out of phase with that at pin 6.)

+6 ± 0.5 vdc shall appear at J3 pin 9

+12 ± 0.2 vdc shall appear at J3 pin 11

-12 ± 0.4 vdc shall appear at J3 pin 12

+20 ± 1 vdc shall appear at J3 pin 14

-20 ± 1 vdc shall appear at J3 pin 15

4.3.2 Pitch Sensor Torque -- Connect J3 pin 6 through 682 kilohms to J2 pin 4. Voltage between J2 pins 17 and 18 shall be 1.7 ± 0.17 vdc, with pin 18 positive. Disconnect the 682-kilohm resistor from J3 pin 6 and reconnect to J3 pin 7. Voltage between J2 pins 17 and 18 shall be 1.7 ± 0.17 vdc, with pin 18 negative.

4.3.3 Roll Sensor Torque -- Connect J3 pin 6 through 682 kilohms to J2 pin 23. Voltage between J2 pins 26 and 27 shall be 1.7 ± 0.17 vdc, with pin 27 positive. Disconnect the 682-kilohm resistor from J3 pin 6 and reconnect to J3 pin 7. Voltage between J2 pins 26 and 27 shall be 1.7 ± 0.17 vdc, with pin 27 negative.

4.3.4 Yaw Sensor Torque -- Connect J3 pin 6 through 682 kilohms to J2 pin 36. Voltage between J2 pins 33 and 34 shall be 1.7 ± 0.17 vdc, with pin 34 positive. Disconnect the 682-kilohm resistor from J3 pin 6 and reconnect to J3 pin 7. Voltage between J2 pins 33 and 34 shall be 1.7 ± 0.17 vdc, with pin 34 negative.

4.3.5 Connect J1 pins 4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, and 22 to J2 pin 2 and connect J1 pin 24 to J3-9. Voltages between J2-17 and 18, J2-26 and 27, and J2-33 and 34 shall fall below 0.3 v in absolute magnitude.

4.4 Normal Limit Operate Mode

4.4.1 Command Torque:

4.4.1.1 +20 deg/sec -- Remove the connections to J2 pins 4,23, and 36. Remove the connections from J1 pins 4, 11, and 17 and connect these pins to J3 pin 9. The voltages between J2 pins 17 and 18, 26 and 27, and 33 and 34 shall become 14.85 ± 0.75 vdc with pins 18, 27, and 34 positive.

4.4.1.2 -20 deg/sec -- Remove the connection to J1 pins 4, 11, and 17 and connect these pins to J1-2. Remove the connections previously made from J1 pins 7,14, and 20, and connect these pins to J3-9. The voltage between J2 pins 17 and 18, 26 and 27, and 33 and 34 shall become 14.85 ± 0.75 vdc, with pins 18,27, and 34 negative.

4.4.1.3 +3 deg/sec -- Remove the connections previously made on J1 pins 7, 14, and 20, and connect these pins to J3-10. Remove the connections to J1 pins 5,12, and 18, and connect these pins to J3-9. The voltage between J2 pins 17 and 18, 26 and 27, and 33 and 34 shall become 2.22 ± 0.11 vdc, with J2 pins 18, 27, and 34 positive.

4.4.1.4 -3 deg/sec -- Remove the connections previously made to pins J1-5, 12, and 18, and connect these pins to J3-10. Remove the connections to J1 pins 8, 15, and 21, and connect these pins to J3-9. The voltage between J2 pins 17 and 18, 26 and 27, and 33 and 34 shall become 2.22 ± 0.11 vdc, with J2 pins 18, 27, and 34 negative.

4.4.1.5 +0.15 deg/sec -- Remove the connections previously made to J1 pins 8, 15, and 21, and connect these pins to J3-10. Remove the connections previously made to J1 pins 6, 13, and 19, and connect these pins to J3-9. The voltage between J2 pins 17 and 18, 26 and 27, and 33 and 34 shall become 0.111 ± 0.011 vdc, with J2 pins 18, 27, and 34 positive.

4.4.1.6 -0.15 deg/sec -- Remove the connections previously made to J1 pins 6, 13, and 19, and connect these pins to J3-10. Remove the connections previously made to J1-pins 9, 16, and 22, and connect these pins to J3-9. The voltage between J2 pins 17 and 18, 26 and 27, and 33 and 34 shall become 0.111 ± 0.011 vdc, with J2 pins 18, 27, and 34 negative.

4.4.2 Translation Command:

Voltage output at J1 pins 41 through 48 shall be 28 vdc from the primary 28 vdc source when J1 pins 4 through 9, 11 through 16, 17 through 22, and 34 through 39 are connected to J3-10.

4.4.2.1 +X, Forward Translation -- Remove the previously made connection from J1-34 and connect J1-34 to J3-9. J1 pins 42, 43, 46, and 47 shall become +1 ± 0.5 vdc. Remove the connection from J1-34 to J3-9 and make the connection J1-34 to J3-10. J1 pins 42, 43, 46, and 47 shall be +28 ± 4 vdc.

4.4.2.2 -X, Aft Translation -- Remove the previously made connection from J1-35 and connect J1-35 to J3-9. J1 pins 41, 44, 45, and 48 shall become +1 ± 0.5 vdc. Remove the connection J1-35 to J3-9 and connect J1-35 to J3-10. J1 pins 41, 44, 45, and 48 shall become +28 ± 4 vdc.

4.4.2.3 +Y, Right Translation -- Remove the previously made connection to J1-36 and connect J1-36 to J3-9. J1 pins 43, 44, 47, and 48 shall become +1 ± 0.5 vdc. Remove the connection J1-36 to J3-9 and make the connection J1-36 to J3-10. J1 pins 43, 44, 47, and 48 shall become +28 ± 4 vdc.

4.4.2.4 -Y, Left Translation -- Remove the previously made connection from J1-37 and make the connection J1-37 to J3-9. J1 pins 41, 42, 45, and 46 shall become +1 ± 0.5 vdc. Remove the connection J1-37 to J3-9 and make the connection J1-37 to J3-10. J1 pins 41, 42, 45, and 46 shall become +28 ± 4 vdc.

4.4.2.5 +Z, Down Translation -- Remove the previously made connection from J1-38 and make the connection J1-38 to J3-9. J1 pins 41, 42, 43, and 44 shall become +1 ± 0.5 vdc. Remove the connection J1-38 to J3-9 and make the connection J1-38 to J3-10. J1 pins 41, 42, 43, and 44 shall become +28 ± 4 vdc.

4.4.2.6 -Z, Up Translation -- Remove the previously made connection from J1-39 and make the connection J1-39 to J3-9. J1 pins 45, 46, 47, and 48 shall become +1 ± 0.5 vdc. Remove the connection J1-39 to J3-9 and make the connection J1-39 to J3-10. J1 pins 45, 46, 47, and 48 shall become +28 ± 4 vdc.

4.4.3 Attitude Stabilization:

The entries in the body of Table III-1 indicate the outputs that shall occur when the system is stimulated by the inputs shown in the input column.

4.4.4 Temperature Control:

Connect the wiper of the potentiometer connected between J2 pins 29 and 30 to J2-30. Adjust the wiper position until the resistance applied between J2 pins 29 and 30 is 770 ohms. A minimum of 18 milliamperes shall flow through the 2.6-ohm resistor connected between J2 pins 8 and 9. Adjust the wiper position until the resistance applied betwen J2 pins 29 and 30 is 790 ohms. A maximum of 10 microamperes shall flow through the 2.6-ohm resistor connected between J2 pins 8 and 9.

Table III-1. Attitude Stabilization Input-Output Relationships

Input*		Output* - Pin J1							
Pin J2	Level and Phase** (v rms)	41	42	43	44	45	46	47	48
4*	∿0.201	28†	1-17†	1-17	28	1-17	28	28	1-17
23	∿0.201	1-17	1-17	28	28	28	28	1-17	1-17
36	∿0.201	28	1-17	28	1-17	28	1-17	28	1-17
4	∽0.201	1-17	28	28	1-17	28	1-17	1-17	28
23	∽0.201	28	28	1-17	1-17	1-17	1-17	28	28
36	∽0.201	1-17	28	1-17	28	1-17	28	1-17	28
4	∿0.25	28	1-37†	1-37	28	1-37	28	28	1-37
23	∿0.25	1-37	1-37	28	28	28	28	1-37	1-37
36	∿0.25	28	1-37	28	1-37	28	1-37	28	1-37
4	∽0.25	1-37	28	28	1-37	28	1-37	1-37	28
23	∽0.25	28	28	1-37	1-37	1-37	1-37	28	28
36	∽0.25	1-37	28	1-37	28	1-37	28	1-37	28
4	∿0.175	28	28	28	28	28	28	28	28
23	∿0.175	28	28	28	28	28	28	28	28
36	∿0.175	28	28	28	28	28	28	28	28
4	∽0.175	28	28	28	28	28	28	28	28
23	∽0.175	28	28	28	28	28	28	28	28
36	∽0.175	28	28	28	28	28	28	28	28

*Input pins are connected to the axis computer inputs. Output pins have simulated solenoid loads connected per Paragraph 4.1.1.

** ∿0.201 v rms is 0.201 v rms 400 cps square wave in phase with J3-6.

∽ 0.25 v rms is 0.25 v rms 400 cps square wave out of phase with J3-6.

†1-17 is +1 ± 0.5 vdc output level for 17 ± 1.7 milliseconds.

1-37 is +1 ± 0.5 vdc output level for 37.7 ± 4 milliseconds.

28 is +28 ± 4 vdc output continuous.

4.5 Extended Limit Operate Mode

Connect J1-25 to J3-9.

4.5.1 Command Torque -- Per 4.4.1.

4.5.2 Translation Command -- Per 4.4.2.

4.5.3 Attitude Stabilization -- Per 4.4.3, except that the 0.201 v rms input signal becomes 1.785 v rms, the 0.25 v rms input signal becomes 2.22 v rms, and the 0.175 v rms input signal becomes 1.555 v rms.

SECTION IV

SPECIFICATION FOR THE ASTRONAUT MANEUVERING UNIT VOICE CONTROLLER BREADBOARD

1.0 SCOPE

This specification contains a technical description of a voice controller to be used by an astronaut in addressing translational or rotational commands to an attitude control system (ACS).

2.0 APPLICABLE DOCUMENTS

a. NASA Contract NASw-841

b. Section I, "Requirements for the Astronaut Maneuvering Unit Attitude Control System," of Appendix A

3.0 REQUIREMENTS

3.1 General Design Requirements

The ACS controller shall be designed to operate from certain specified voice outputs of the astronaut. Unnatural variations of those outputs in volume or pitch shall not have a detrimental effect on controller operation. The controller shall not interfere with normal voice communication, with the environmental support system, or with the visual and mobility functions of the astronaut

3.1.1 Three functions shall be included: voice input, speech recognition, and control signal generation.

3.1.2 A microphone system shall be used, whether of the close-talking or contact type, that has the sensitivity, fidelity, frequency response, and dynamic range characteristics necessary to transduce the speech commands specified in Paragraph 3.2.1 reliably and without distortion.

3.2 Functional Characteristics

3.2.1 The controller shall respond to the following words, uttered as vocal inputs:

Roll	X	Plus	Stop
Pitch	Y	Minus	Cage
Yaw	Z		

The controller shall not respond to any other vocal inputs.

3.2.2 Rotational Control

3.2.2.1 The astronaut shall select a rotation maneuver by uttering one of the following three terms: roll, pitch, yaw. These terms shall correspond to body rotations about the x, y, and z axes, respectively. Any rotation command can be changed to any other maneuver command prior to its execution.

3.2.2.2 Speed selection shall be performed by uttering the maneuver word in a repetitive manner, as follows:

Maneuver Word	Rotation Rate
Uttered once	Precision
Uttered twice	Low
Uttered three times	High

3.2.2.3 A direction for the maneuver shall be selected by uttering the word "plus" or "minus". Such utterance shall normally occur immediately following the maneuver and speed command utterances.

3.2.2.4 The direction command shall also constitute the execution command for the ACS, such that its utterance will cause the ACS to perform the desired rotation maneuver at the speed and direction commanded.

3.2.2.5 The duration of the rotation maneuver shall be governed by repetitions of the execution (direction) command. The maneuver shall be sustained as long as the appropriate command is repeated. The rate of repetition required to sustain a maneuver shall not be greater than one word per second.

3.2.3 Translational Control

3.2.3.1 The astronaut shall select a translation maneuver by uttering one of the following three terms: X, Y, Z. The terms shall correspond to body translations along the x, y, and z axes, respectively. Any translation command can be changed to any other maneuver command prior to its execution.

3.2.3.2 Acceleration selection shall be performed by uttering the maneuver word in a repetitive manner, as follows:

Maneuver Word	Translation Acceleration
Uttered once	Low
Uttered twice	High

3.2.3.3 A direction for the maneuver shall be selected by uttering the word "plus" or "minus". Such utterance shall normally occur immediately following the maneuver and acceleration command utterances.

3.2.3.4 The direction command shall also constitute the execution command for the ACS, such that this utterance will cause the ACS to perform the desired translation maneuver at the acceleration and direction commanded.

3.2.3.5 The duration of the translation maneuver shall be governed by repetitions of the execution (direction) command. The maneuver shall be sustained as long as the appropriate command is repeated. The rate of repetition required to sustain a maneuver shall not be greater than one word per second.

3.2.4 Stop Control

3.2.4.1 The single word "stop", uttered at any time, shall immediately remove all verbal commands from the ACS system. The translational system shall revert to Coast mode, and the ACS shall revert to attitude hold using as a reference the attitude that existed at the time the "stop" command was given.

3.2.4.2 No release or engage function by the operator shall be necessary for the system to accept new commands after the "stop" command has been given. Normal operation should resume when a normal verbal command sequence is given.

3.2.5 Gyro Caging Control

3.2.5.1 The phrase "stop-cage", uttered at any time, shall immediately remove all verbal commands from the ACS and place the gyros in an attitude synchronous mode of operation. Reaction jet operation shall be prevented.

3.2.5.2 No release or engage function by the operator shall be necessary for the system to accept new commands after the cage command has been given. Normal operation should resume when a normal verbal command sequence is given. Attitude reference shall be that existing at the time the cage command was given, provided angular rates were less than 20 deg/sec.

3.2.6 Deadband Control

3.2.6.1 The phrase "stop-plus", uttered at any time during normal operation, shall immediately provide the ACS with wide (±10 degrees) deadband limits in all body axes. The ACS shall retain the wide limits until the astronaut selects the narrow deadband limits as specified in Paragraph 3.2.6.2 or until a precision rate of rotation is commanded.

3.2.6.2 The phrase "stop-minus", uttered at any time during normal operation, shall immediately provide the ACS with narrow (±0.8 degree) deadband limits in all body axes. The ACS shall retain the narrow limits until the astronaut selects the wide deadband limits as specified in Paragraph 3.2.6.1. The narrow limits shall be removed and the system shall revert to the wide limits any time the ACS is placed in the caged mode.

3.3 Performance Characteristics

3.3.1 The dynamic range of the speech controller shall be 30 db. It shall provide normal signal inputs to the ACS when the operator's voice intensity varies over a range corresponding to sound pressure levels from 59 to 89 db one meter from the speaker.

3.3.2 The response time of the voice input and speech recognition functions shall be such that appropriate electrical outputs shall result from the 10 permissible vocal inputs in 0.1 second or less, measured peak-to-peak (speech peak-to-signal peak).

3.4 Electrical Characteristics

3.4.1 The thrust logic outputs of the controller to the ACS sensors and electronics shall be designated:

O - Positive x-axis acceleration
P - Negative x-axis acceleration

Q - Positive y-axis acceleration
R - Negative y-axis acceleration
S - Positive z-axis acceleration
T - Negative z-axis acceleration

3.4.2 Logic Designation

The controller shall switch a given logic output from 0 to 1 by changing the characteristics of the voltage applied to a wire according to the following:

State	Voltage (vdc)	Source Impedance (K ohm max)
0	0 ± 0.5	4.5
1	$+6 \pm 0.5$	4.5

3.4.3 There shall be 20 torquing commands to the electronics consisting of voltages with the characeristics given in Paragraph 3.4.2:

ACS OFF	Pitch Hi Neg
Yaw Hi Pos	Pitch Lo Neg
Yaw Lo Pos	Pitch Precision Neg
Yaw Precision Pos	Roll Hi Pos
Yaw Hi Neg	Roll Lo Pos
Yaw Lo Neg	Roll Precision Pos
Yaw Precision Neg	Roll Hi Neg
Pitch Hi Pos	Roll Lo Neg
Pitch Lo Pos	Roll Precision Neg
Pitch Precision Pos	Deadband Set

3.5 Physical Characteristics

3.5.1 The voice controller breadboard, which shall be taken to include the voice input section, the speech analyzer section, and the signal output section, shall not exceed 1.5 cubic feet in volume.

3.5.2 The voice controller, as defined in Paragraph 3.5.1, shall not weigh more than 20 pounds.

3.5.3 A design goal shall be to use parts suitable for use in a space qualified device.

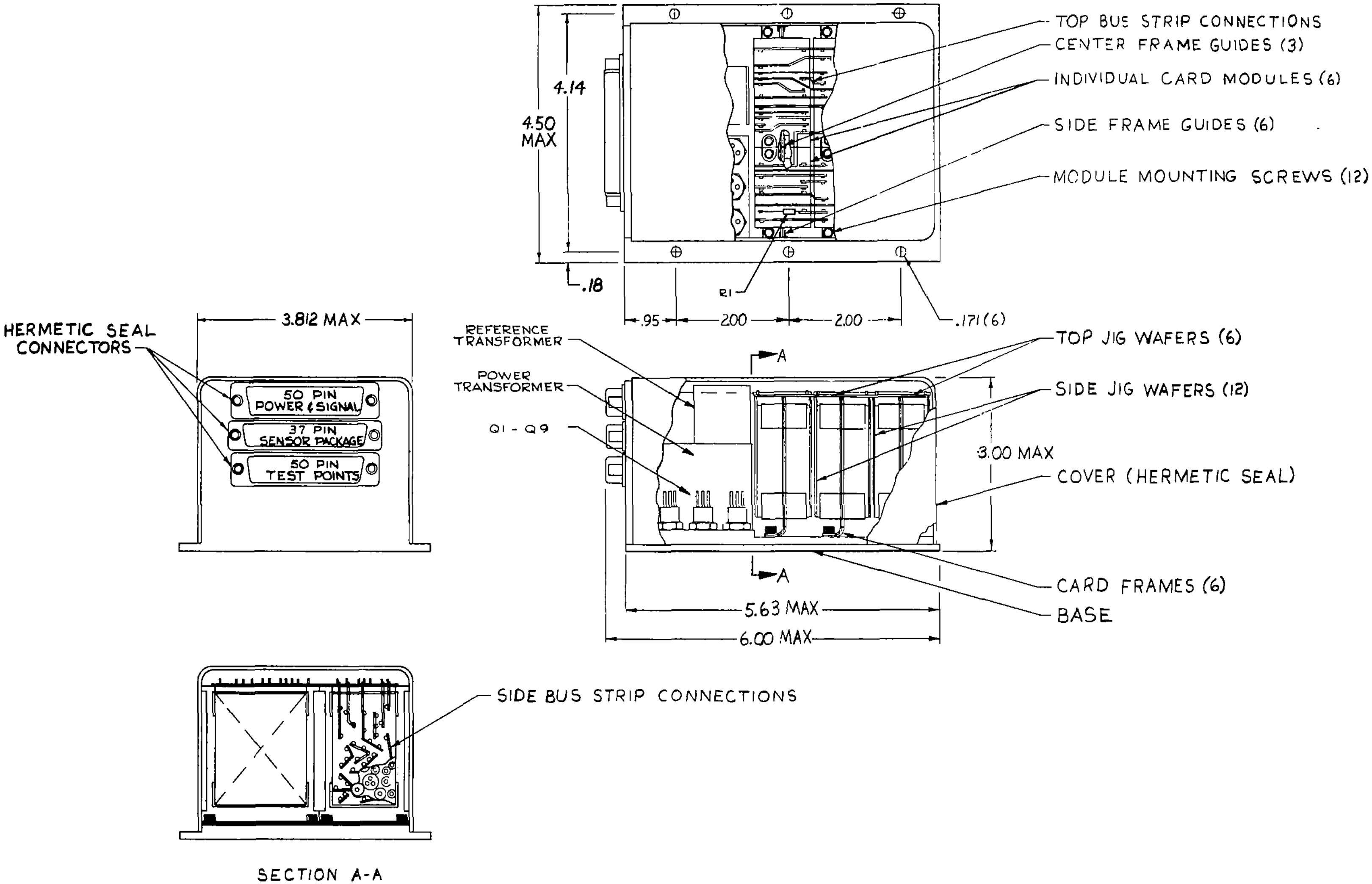
4.0 BREADBOARD TESTS

4.1 Selected environmental tests shall be performed to assure that the design is suitable for use in a space environment.

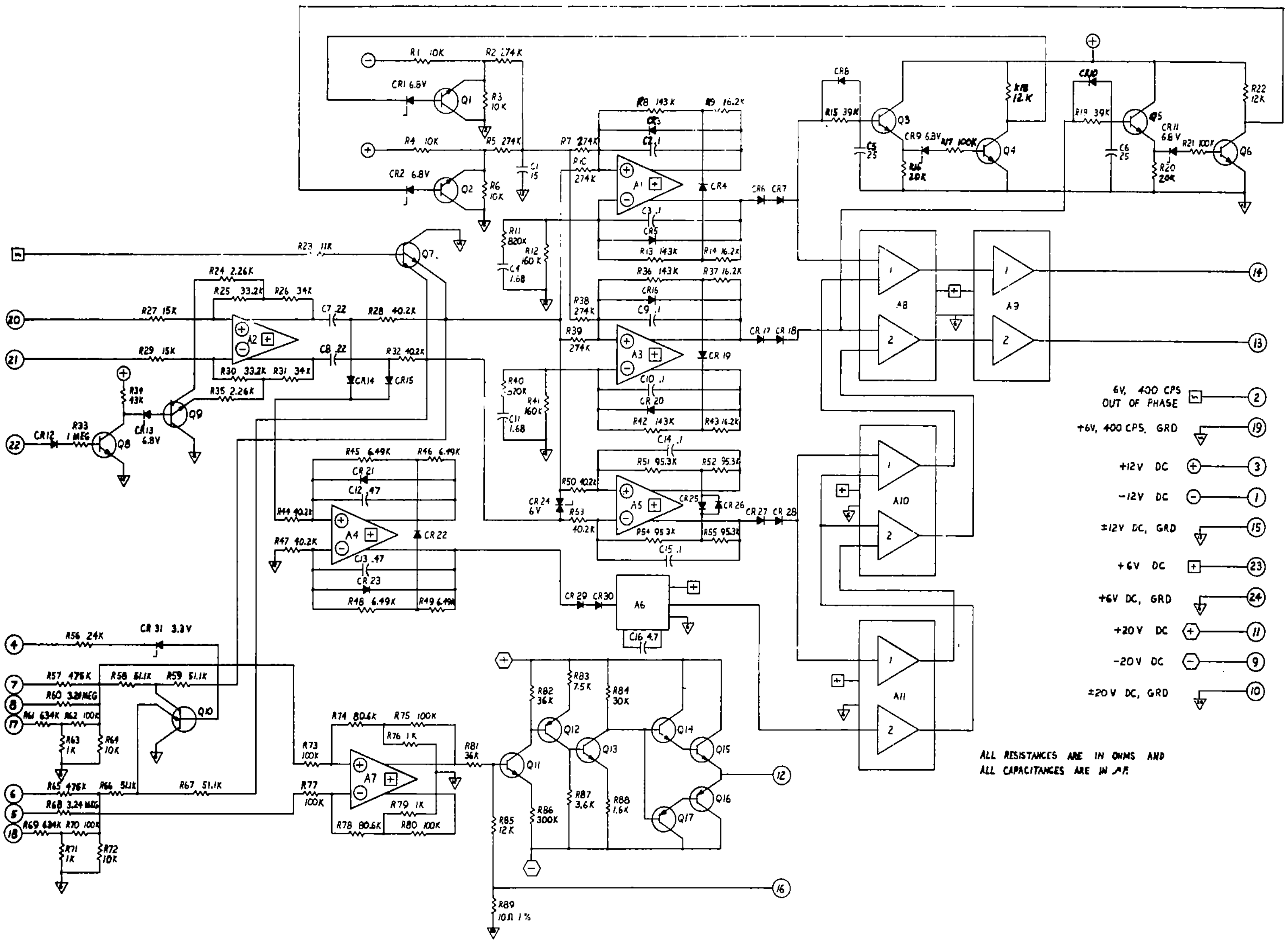
4.2 Tests performed shall be consistent with the degree to which components suitable for space use are used in the breadboard equipment.

APPENDIX B

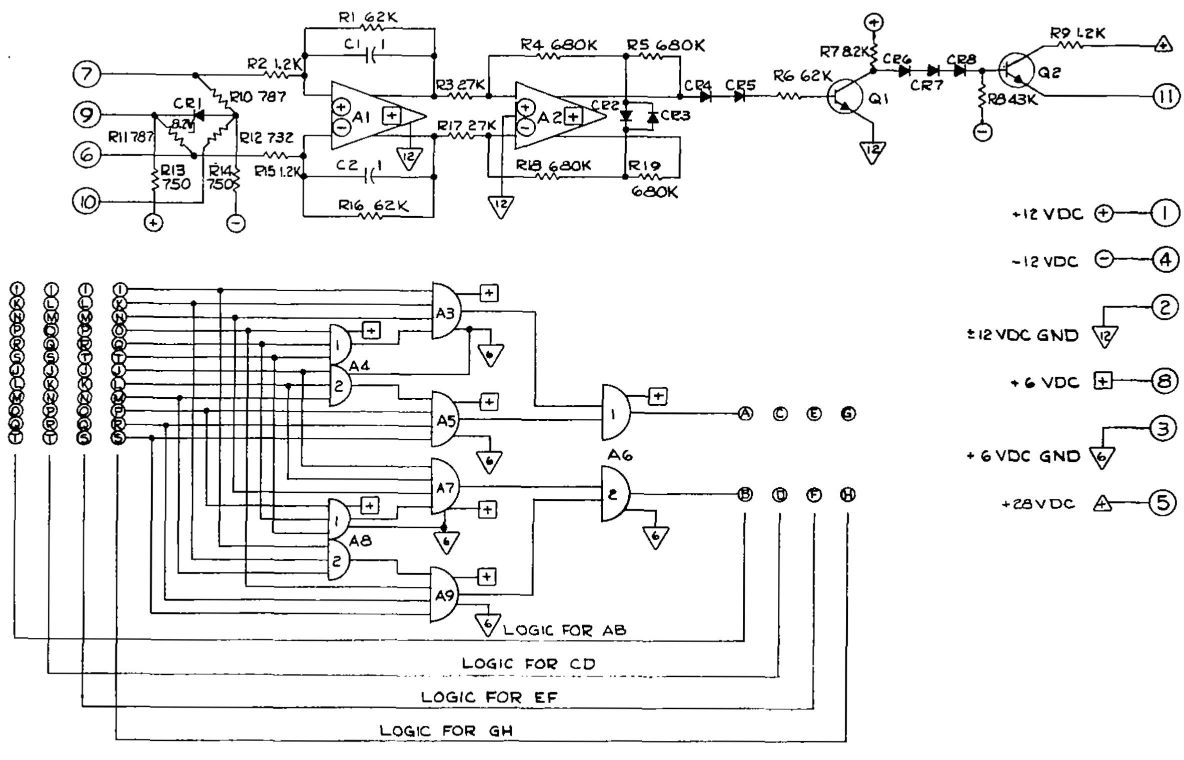
DRAWINGS



Control Electronics Package Installation Drawing, SK92538



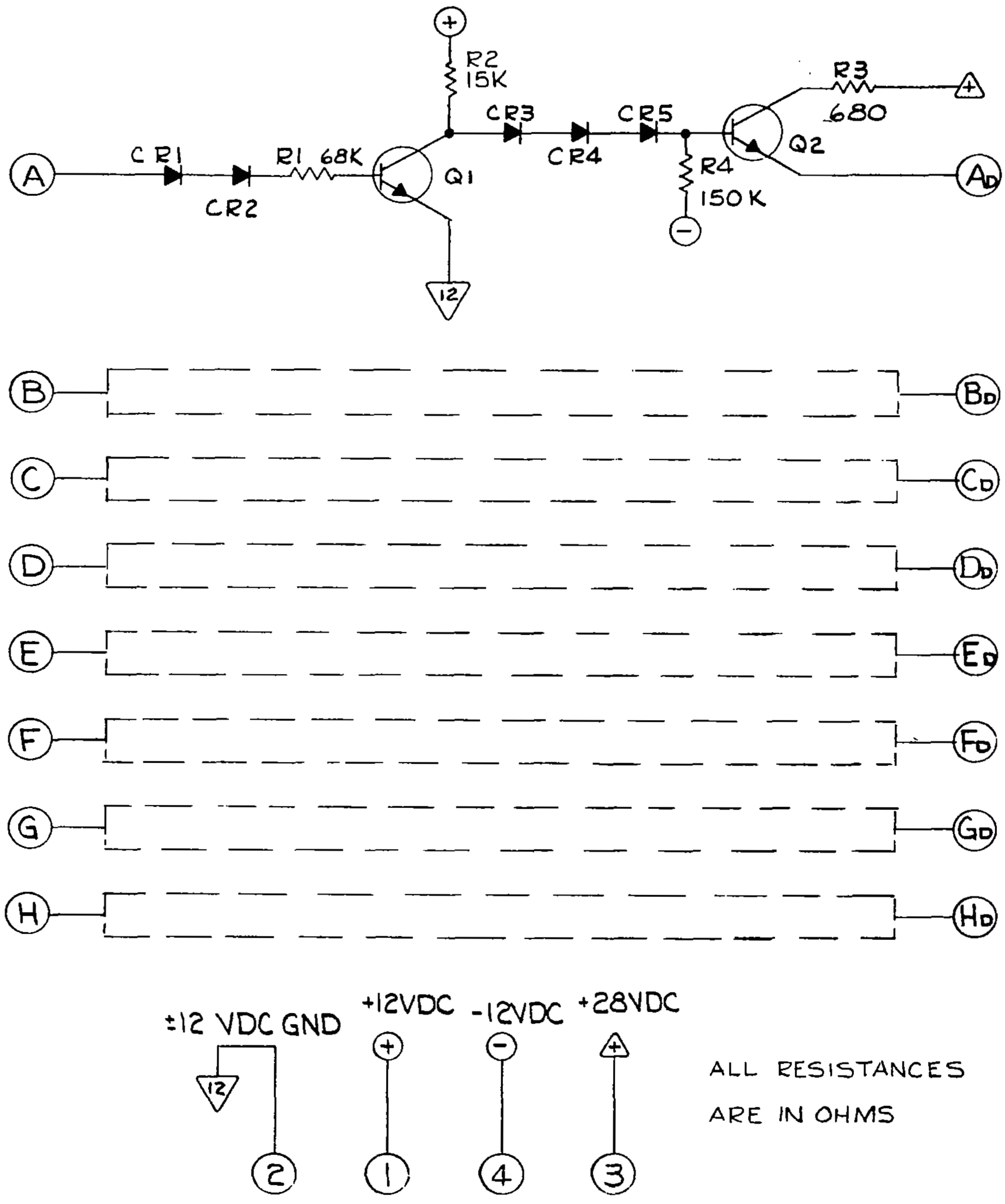
Control Electronics Package Circuit Drawing
Welded Module Roll Computer, SK92531
Welded Module Pitch Computer, SK92532
Welded Module Yaw Computer, SK92533



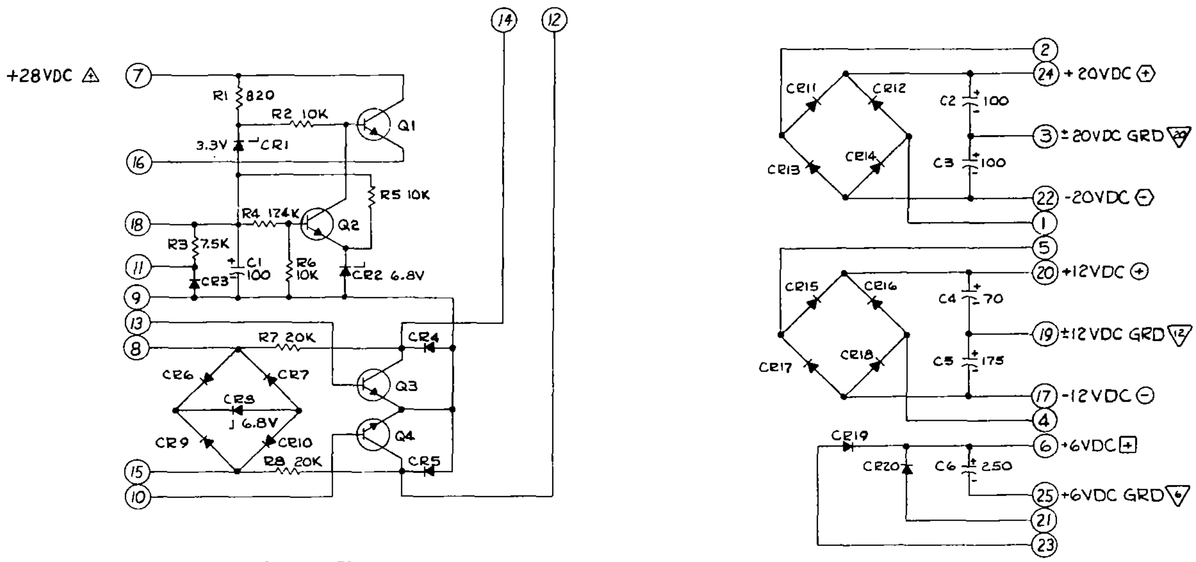
ALL RESISTANCES ARE IN OHMS AND ALL CAPACITANCES ARE IN UF

Control Electronics Package Circuit Drawing, Welded Module Logic and TCA, SK92529

ALL CIRCUITS IDENTICAL

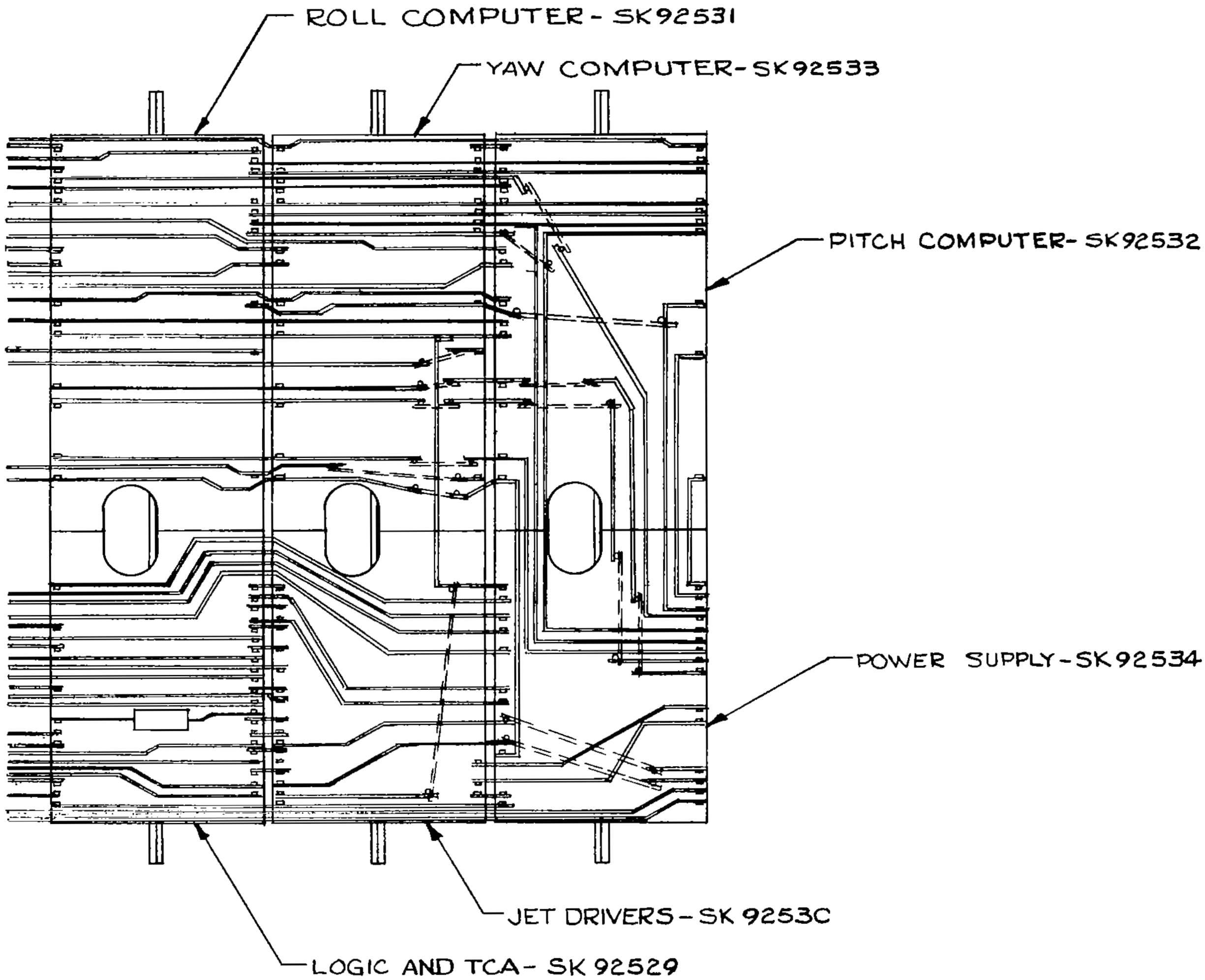


Control Electronics Package Circuit Drawing,
Welded Module Jet Drivers, SK92530

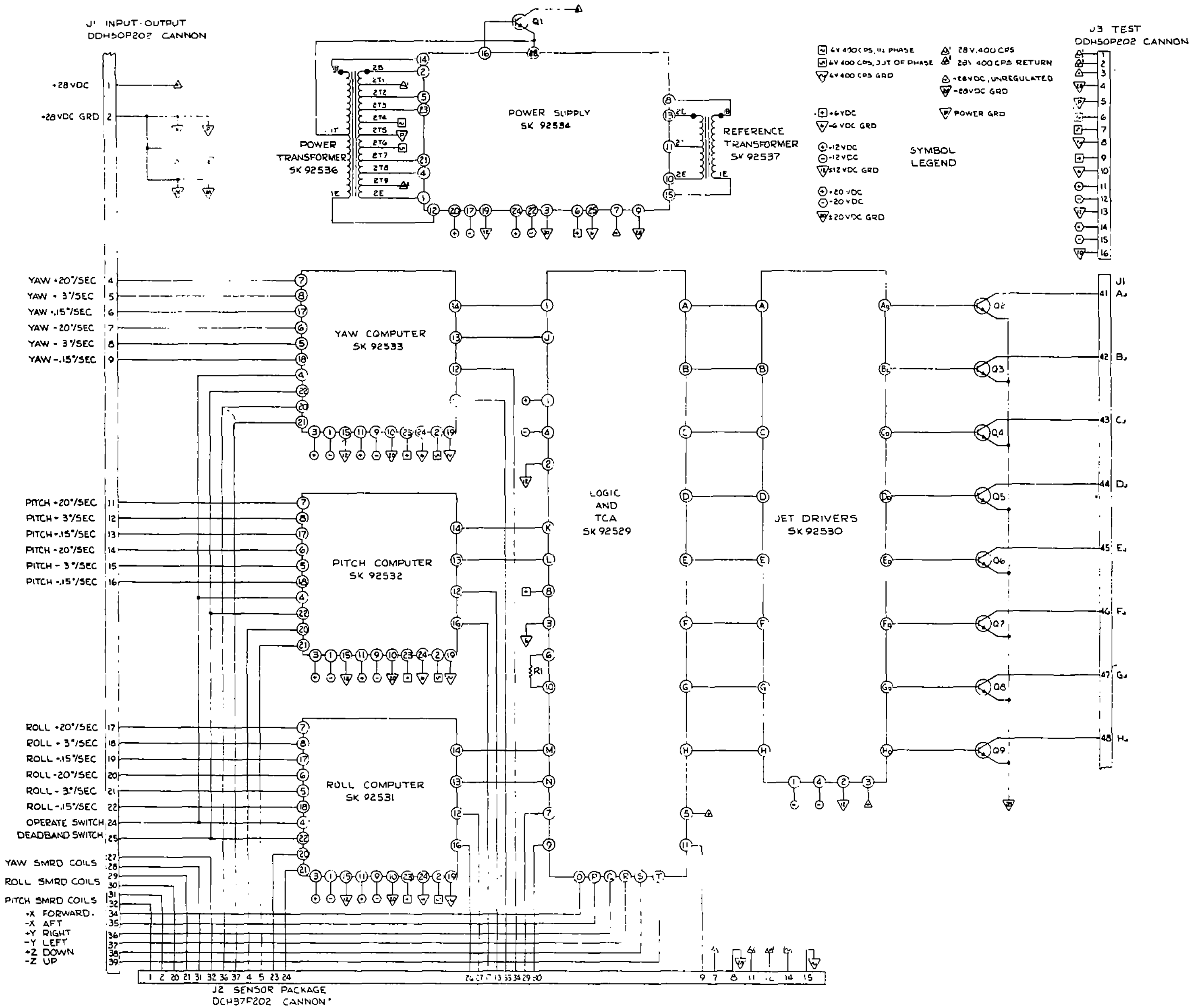


ALL RESISTANCES ARE IN OHMS AND ALL CAPACITANCES ARE IN UF

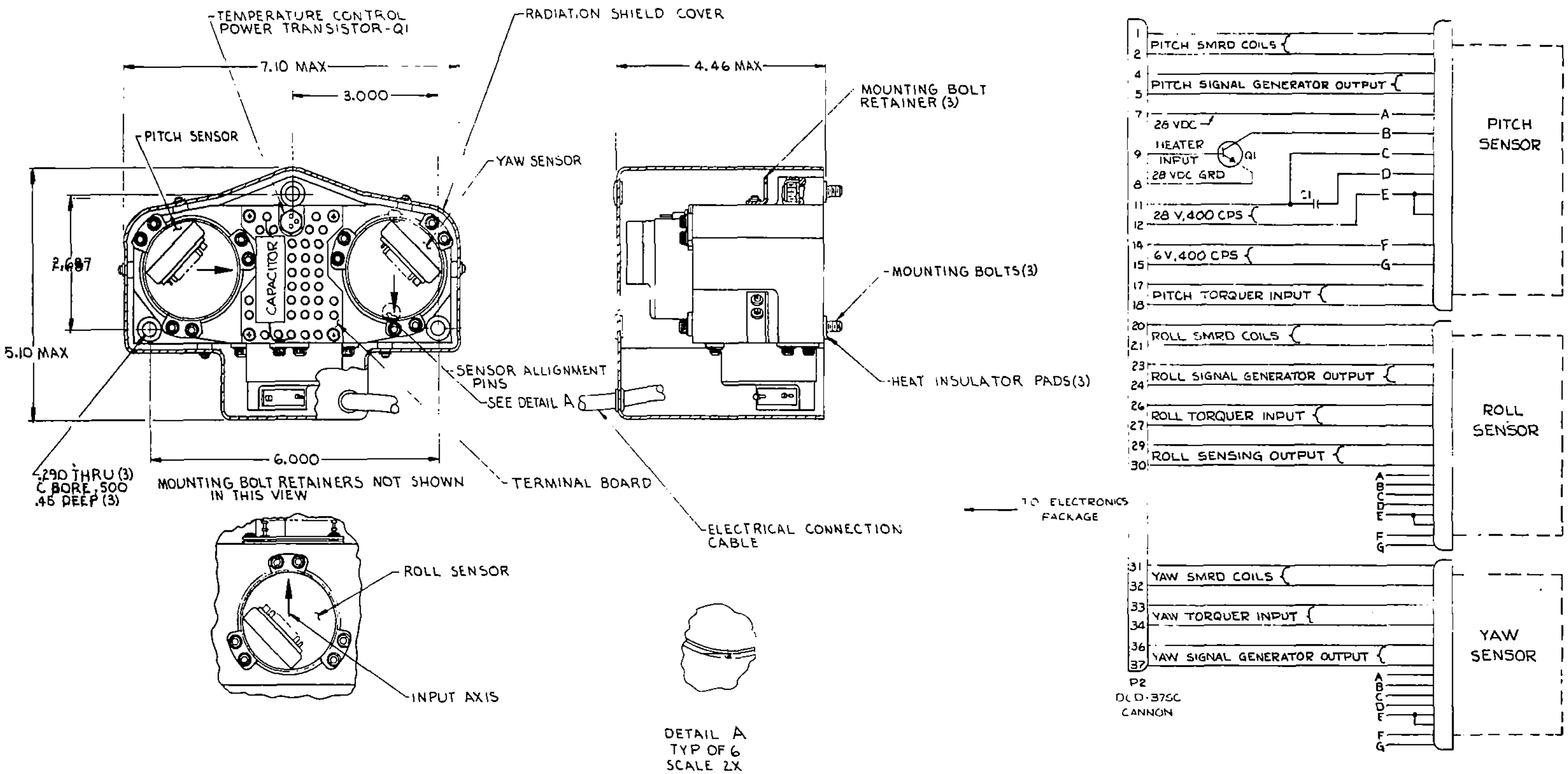
Control Electronics Package Circuit Drawing, Welded Module Power Supply, SK92534



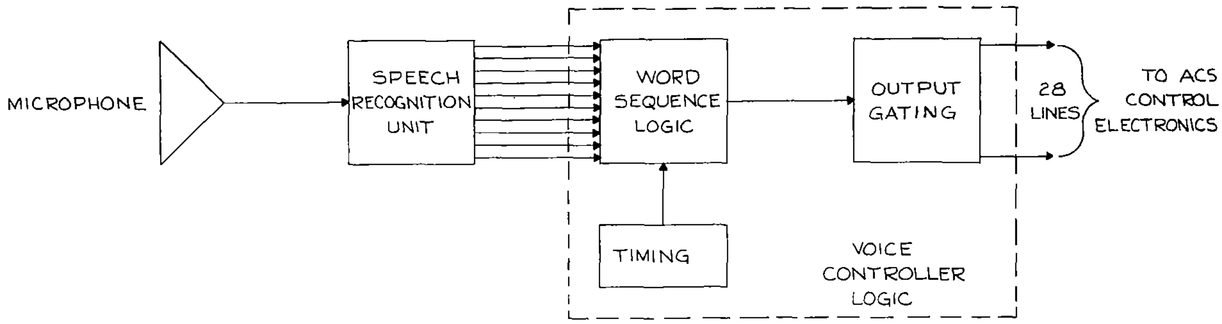
Control Electronics Package Circuit Drawing, Assembly of Jig Wafer, SK92535



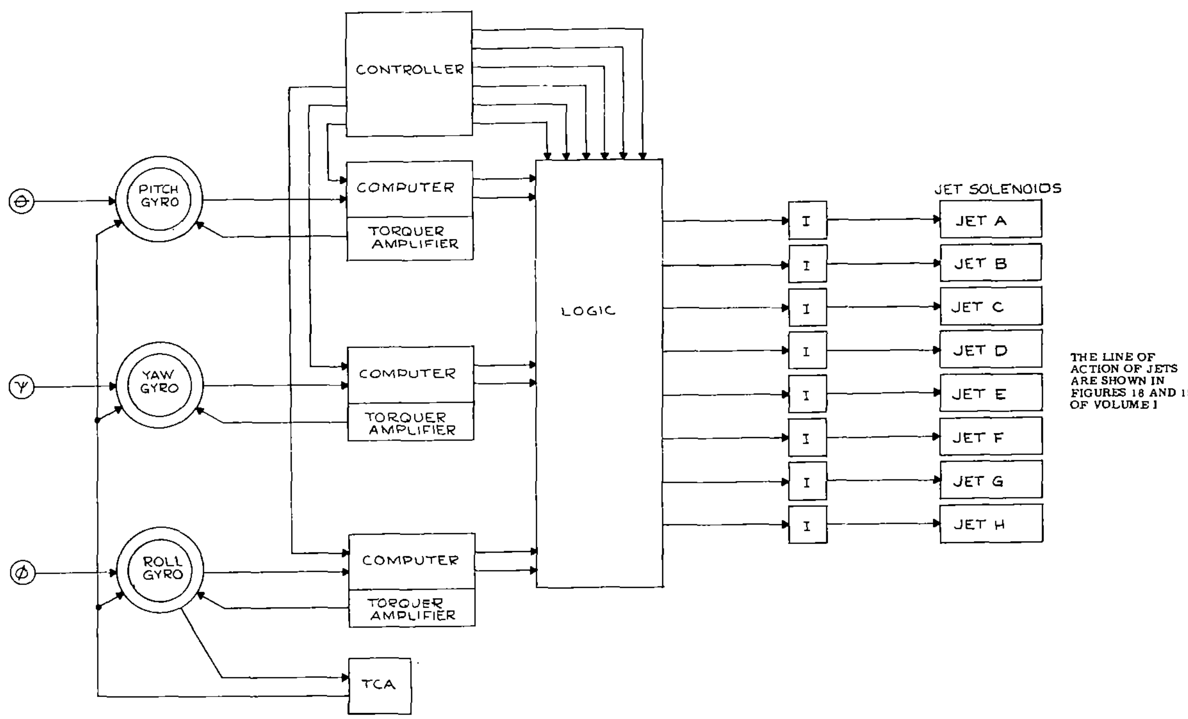
AMU-ACS Electronics Package Schematic, SK92539



Sensor Package Installation Drawing and Schematic, SK92540



Voice Controller Flow Diagram, SK92542



System Flow Diagram, SK92541

PARTS LISTS

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK92538	AMU-ACS ELECTRONICS	1	—	1781-04	1 OF 1

DEVICE NO.	DEVICE NAME	DEV. QUANTITY	P.E. AUTH.	REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
DY6970A1	AMU-ACS			ISSUED								

PROJECT ENGR'S AUTH. TO BUY/FAB

A – ASSEMBLY 0 – PIECE PART

ITEM	MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	PART CODE	PART NUMBER	PART NAME	USAGE / ASSEMBLY	REMARKS	SHEET REV. LETTER
1						A	SK92529	LOGIC & TCA	1		
2						A	SK92530	JET DRIVERS	1		
3						A	SK92531	ROLL COMPUTER	1		
4						A	SK92532	PITCH COMPUTER	1		
5						A	SK92533	YAW COMPUTER	1		
6						A	SK92534	POWER SUPPLY	1		
7						0	SK92535	JIG WAFER	1		
8						0	SK92536	TRANSFORMER, POWER	1		
9						0	SK92537	TRANSFORMER, REF	1		
10						0	MHT 6414	TRANSISTOR	9		
11						0	DDH50P202	CONNECTOR	2	50 PIN, HERMETIC SEAL CANNON	
12						0	DCH37P202	"	1	37 PIN, HERMETIC SEAL CANNON	
13						0	RN60BXXXXF	RESISTOR	1	R1 SELECT	

* IF INITIALED: INDICATES ENG. AUTH. TO USE APPLICABLE ENG. DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK 92531	ROLL COMPUTER	1	SK 92538	1781-04	1 OF 4

DEVICE NO.	DEVICE NAME	DEV. QUANTITY	P.E. AUTH.	REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
DYG 970A1	AMU-ACS			ISSUED								

PROJECT ENGR'S AUTH. TO BUY/FAB

A – ASSEMBLY 0 – PIECE PART

ITEM	MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	PART CODE	PART NUMBER	PART NAME	USAGE/ASSEMBLY	REMARKS	SHEET REV. LETTER
1						0	RC07GF103J	RESISTOR	4	10K, 1/4w, 5% R1, R3, R4, R6	
2						0	RN55D2743F	"	6	274K, 1/10w, 1% R2, R5, R7, R10, R38, R39	
3						0	RN55D1433F	"	4	143K, 1/10w, 1%, R8, R13, R36, R42.	
4						0	RN55D1622F	"	4	16.2K, " ", R9, R14, R37, R43	
5						0	RC07GF824J	"	2	820K, 1/4w, 5%, R11, R40	
6						0	RC07GF164J	"	2	160K, " ", R12, R41	
7						0	RC07GF393J	"	2	39K, " ", R15, R19	
8						0	RC07GF203J	"	2	20K, " ", R16, R20	
9						0	RC07GF104J	"	2	100K, " ", R17, R21	
10						0	RC07GF123J	"	3	12K, " ", R18, R22, R85	
11						0	RC07GF113J	"	1	11K, " ", R23	
12						0	RN55D2261F	"	2	2.26K, 1/10w, 1%, R24, R35	
13						0	RN55D3322F	"	2	33.2K, ", R25, R30	
14						0	RN55D3402F	"	2	34K, " ", R26, R31	
15						0	RN55D1502F	"	2	15K, 1/10w, 1%, R27, R29	
16						0	RC07GF105J	"	1	1 MEG, 1/4w, 5%, R33	
17						0	RC07GF433J	"	1	43K, " ", R34	
18						0	RN55D6491F	"	4	6.49K, 1/10w, 1%, R45, R46, R48, R49,	

* IF INITIALED: INDICATES ENG. AUTH. TO USE APPLICABLE ENG. DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK 92531	ROLL COMPUTER	1	SK 92538	1781-04	2 OF 4

DEVICE NO.	DEVICE NAME	DEV. QUANTITY	P.E. AUTH.	REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
DYG 970A1	AMU - ACS			ISSUED								

PROJECT ENGR'S AUTH. TO BUY/FAB — A - ASSEMBLY; O - PIECE PART

ITEM	MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	PART CODE	PART NUMBER	PART NAME	USAGE/ASSEMBLY	REMARKS	SHEET REV. LETTER
19						O	RN55D9532F	RESISTOR	4	95.3K, 1/10 w, 1%, R51, R52, R54, R55	
20						O	RC07GF243J	"	1	24K, 1/4 w, 5%, R56	
21						O	RN55D4753F	"	2	475K, 1/10 w, 1%, R57, R65	
22						O	RN55D5112F	"	4	51.1K, " ", R58, R59, R66, R67	
23						O	RN55D3244F	"	2	3.24 MEG, " ", R60, R68	
24						O	RN55D4022F	"	6	40.2K, 1/10 w, 1%, R28, R32, R44, R47, R50, R53	
25						O	RN55D6343F	"	2	634K, " ", R61, R69	
26						O	RN55D1003F	"	6	100K, " ", R62, R70, R73, R75, R77, R80	
27						O	RN55D1001F	"	4	1K, " ", R63, R71, R76, R79	
28						O	RN55D1002F	"	2	10K, " ", R64, R72	
29						O	RN55D8062F	"	2	80.6K, " ", R74, R78	
30						O	RC07GF363J	"	2	36K, 1/4 w, 5%, R81, R82	
31						O	RC07GF752J	"	1	7.5K, " ", R83	
32						O	RC07GF303J	"	1	30K, " ", R84	
33						O	RC07GF304J	"	1	300K, " ", R86	
34						O	RC07GF362J	"	1	3.6K, " ", R87	
35						O	RC07GF162J	"	1	1.6K, " ", R88	
36						O	RC07GF100J	"	1	10Ω, 1/10 w, 1%, R89	

* IF INITIALED: INDICATES ENG. AUTH. TO USE APPLICABLE ENG. DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK 92531	ROLL COMPUTER	1	SK 92538	1781-04	3 OF 4

DEVICE NO.	DEVICE NAME	DEV. QUANTITY	P.E. AUTH.	REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
DYG 970A1	AMU- ACS			ISSUED								

A – ASSEMBLY 0 – PIECE PART

ITEM	PROJECT ENGR'S AUTH. TO BUY/FAB: MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	PART CODE	PART NUMBER	PART NAME	USAGE / ASSEMBLY	REMARKS	SHEET REV. LETTER
37						0	956488-9	DIODE, ZENER	5	6.8V, CR1, CR2, CR9, CR11, CR13	
38						0	956487-1	DIODE	24	CR3-CR8, CR10, CR14-CR23, CR25-CR30, CR12	
39						0	1N824	DIODE, ZENER	1	6.0V, CR24	
40						0	956488-1	" "	1	3.3V, CR31	
41						0	NL15	CAPACITOR, NP	1	15 uF @ 6V, C1 COMPONENTS, INC	
42						0	NTR10	" "	6	.1 uF @ 20V, C2, C3, C9, C10, C14, C15 COMPONENTS, INC	
43						0	NF1R68	" "	2	1.68 uF @ 6V, C4, C11 COMPONENTS, INC	
44						0	62F201	CAPACITOR, POLAR	2	25 uF @ 8V, C5, C6 G.E.	
45						0	NTR22	CAPACITOR, NP	2	.22 uF @ 15V, C7, C8 COMPONENTS, INC	
46						0	NTR47	" "	2	.47 uF @ 8V, C12, C13 " "	
47						0	NM4R7	" "	1	4.7 uF @ 6V, C16 " "	
48						0	960063	TRANSISTOR	2	2N2432, Q1, Q2	
49						0	956686-2	"	8	2N930, Q3-Q6, Q8, Q11, Q13, Q14	
50						0	3N76	"	3	3N76, Q7, Q9, Q10	
51						0	2N2906	"	2	2N2906, Q12, Q17	
52						0	960595-1	"	1	2N1613, Q15	
53						0	2N3904	"	1	2N2904, Q16	
54						0	SN351A	AMPLIFIER	6	A1-A5, A7 T.I.	

* IF INITIALED: INDICATES ENG. AUTH. TO USE APPLICABLE ENG. DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK 92531	ROLL COMPUTER	1	SK 92538	1781-04	4 OF 4

DEVICE NO.	DEVICE NAME	DEV. QUANTITY	P.E. AUTH.	REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
DVG 970A1	AMU-ACS			ISSUED								

A – ASSEMBLY   0 – PIECE PART

ITEM	PROJECT ENGR'S AUTH. TO BUY/FAB: MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	PART CODE	PART NUMBER	PART NAME	USAGE/ASSEMBLY	REMARKS	SHEET REV. LETTER
55						0	SN518A	ONE SHOT	1	A6 T.I.	
56						0	SN514	DUAL NAND GATE	4	A8 - A11 "	

* IF INITIALED: INDICATES ENG.AUTH.TO USE APPLICABLE ENG.DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY

Parts authorization lists for the pitch computer (SK92532) and yaw computer (SK92533) are identical with the parts authorization list for the roll computer shown on the preceding four pages.

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK 92534	Power Supply	1	SK 92538	1781-04	1 OF 1

DEVICE NO.	DEVICE NAME	DEV.QUANTITY	P.E.AUTH.	REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
DYG 970A1	AMU-ACS			ISSUED								

A – ASSEMBLY 0 – PIECE PART

ITEM	PROJECT ENGR'S AUTH. TO BUY/FAB: MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	PART CODE	PART NUMBER	PART NAME	USAGE / ASSEMBLY	REMARKS	SHEET REV. LETTER
1						0	RC42GF821J	Resistor	1	R1 2W 5%, 820Ω	
2						0	RC07GF103J	"	3	R2, R5, R6, 1/4W, 5%, 10K	
3						0	RC07GF752J	"	1	R3, " 7.5K	
4						0	RN55D1742F	"	1	R4, 1/8W, 1%, 17.4K	
5						0	RC07GF203J	"	2	R7, R8, 1/4W, 5%, 20K	
6						0	956488-1	Diode, Zener	1	CR1, 3.3V	
7						0	956488-9	" , "	2	CR2, CR8, 6.8V	
8						0	953663-1	Diode	17	CR3-CR7, CR9-CR20	
9						0	62F403	Capacitor	3	C1, C2, C3, 100 UF @ 30V, G.E	
10						0	62F302	"	1	C4, 70 UF @ 15V G.E.	
11						0	62F402	"	1	C5, 175 UF @ 15V G.E.	
12						0	62F401	"	1	C6, 250 UF @ 10V G.E	
13						0	956686-2	Transitor	2	Q1, Q2, 2N930	
14						0	MHM2001	"	2	Q3, Q4,	

* IF INITIALED: INDICATES ENG. AUTH. TO USE APPLICABLE ENG. DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK 92530	JET DRIVERS	1	SK 92538	1781-04	1 OF 1

DEVICE NO.	DEVICE NAME	DEV.QUANTITY	P.E.AUTH.	REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
DYG 970A1	AMU-ACS			ISSUED								

SHEET REV. LETTER

A – ASSEMBLY 0 – PIECE PART

ITEM	PROJECT ENGR'S AUTH.TO BUY/FAB MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	CODE	PART NUMBER	PART NAME	USAGE/ASSEMBLY	REMARKS
1						0	956487-1	DIODE	40	CR1-CR5
2						0	RC07GF683J	RESISTOR	8	R1, 1/4 w, 5%, 68K
3						0	RC07GF154J	"	8	R4 " " , 150K
4						0	RL20AD681J	"	8	R3, 1/2 w, " , 680 Ω
5						0	956686-2	TRANSISTOR	16	2N930 Q1, Q2
6						0	RC07GF153J	RESISTOR	8	R2, 1/4 w, 5%, 15K

* IF INITIALED: INDICATES ENG.AUTH.TO USE APPLICABLE ENG.DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK 92529	LOGIC AND TCA	1	SK 92538	1781-04	1 OF 1

DEVICE NO.	DEVICE NAME	DEV.QUANTITY	P.E.AUTH.	REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
DYG 970A1	AMU-ACS			ISSUED								

PROJECT ENGR'S AUTH.TO BUY/FAB — A – ASSEMBLY 0 – PIECE PART

ITEM	MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	PART CODE	PART NUMBER	PART NAME	USAGE/ASSEMBLY	REMARKS	SHEET REV. LETTER
1						0	SN351A	AMPLIFIER	2	A1, A2 T.I.	
2						0	SN514	DUAL NOR GATE	12	A4, A6, A8 T.I.	
3						0	SN512	NAND GATE	16	A3, A5, A7, A9 T.I.	
4						0	RC07GF623J	RESISTOR	3	R1, R6, R16 1/4 w, 5%, 62K	
5						0	RC07GF122J	"	2	R2, R15, " ", 1.2K	
6						0	RC07GF273J	"	2	R3, R17, " ", 27K	
7						0	RC07GF684J	"	4	R4, R5, R18, R19, " ", 680K	
8						0	RC07GF822J	"	1	R7, " ", 8.2K	
9						0	RC07GF433J	"	1	R8, " ", 43K	
10						0	RN60B7870F	"	2	R10, R11, 1/8 w, 1%, 787Ω	
11						0	939491-84	CAPACITOR	2	C1, C2, 1uf @ 100 V	
12						0	956488-11	DIODE, ZENER	1	CR1, 8.2V	
13						0	956487-1	DIODE	7	CR2 - CR8	
14						0	RC20GF122J	RESISTOR	1	R9, 1/2 w, 5%, 1.2K	
15						0	RN60B7320F	"	1	R12, 1/8 w, 1%, 732Ω	
16						0	RC07GF751J	"	2	R13, R14, 1/4 w, 5%, 750Ω	
17						0	956686-2	TRANSISTOR	2	Q1, Q2, 2N930	

* IF INITIALED: INDICATES ENG.AUTH.TO USE APPLICABLE ENG.DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY

PARTS AUTHORIZATION LIST

MPG-4019

ASSY. NO.	ASSY. NAME	ASSYS./DEVICE	NEXT ASSY.	PROJECT NO.	SHEET
SK 92540	AMU-ACS SENSOR	1	—	1781-04	1 OF 1

DEVICE NO.	DEVICE NAME	DEV.QUANTITY	P.E.AUTH.
DYG 970A1	AMU-ACS		

REV.	DATE	ERS	REV.	DATE	ERS	REV.	DATE	ERS
ISSUED								

A — ASSEMBLY O — PIECE PART

ITEM	PROJECT ENGR'S AUTH. TO BUY/FAB: MODEL SHOP PLAN DATE	MODEL SHOP INTLS.	PRODUCTION* PLAN DATE	PRODUCTION* INTLS.	DRAWING RELEASED	PART CODE	PART NUMBER	PART NAME	USAGE/ASSEMBLY	REMARKS	SHEET REV. LETTER
1						A	SK92540-801	GYRO PACKAGE	1		
2						O	939491-XX	CAPACITOR	1		
3						O	MHT 6414	TRANSISTOR	1	Q1	
4						A	SK92540-802	TERMINAL BOARD	1		
5						O	DCD-37SC	CONNECTOR	1	37 PIN, ENVIRONMENTAL CANNON	

* IF INITIALED: INDICATES ENG. AUTH. TO USE APPLICABLE ENG. DATA
IF BLANK: AVAILABLE DATA MAY BE USED FOR PLANNING ONLY